Mathematical Simulation Process Increasing Energy Efficiency of Ship Steam Boilers

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Abstract

The article presents an analysis of the possibility of using a high efficiency of steam boilers for the consumption of heat losses from a marine auxiliary steam boiler of the Mitsubishi MAC brand with a steam productivity of 35 tons of steam per hour. It has been established that control and reduction of air suction into the furnace and flue of the boiler with simultaneous correction of the excess air coefficient makes it possible to increase the efficiency of the boiler up to 7%, depending on the operating mode, compared to a boiler not equipped with an air suction control system.

Keywords

Mathematical simulation, energy efficiency, steam boiler, efficiency factor, heat loss, simplex method for optimizing environmental parameters

1. Introduction

It is known that the working process that takes place in a ship's steam generator or steam boiler is complex. It can be considered as consisting of separate processes occurring in the air-gas and steam-water paths of the boiler. The steam capacity of modern main marine boilers can range from 20 to 250 t/h or more, auxiliary boilers, on average, from 0.5 to 80 t/h. The operating steam pressure in modern main steam generators can range from 2.5 to 9 MPa. The superheated steam temperature is in the range from 350 to 560 ^{0}C [1,2,3].

The disadvantage of the existing methods for modeling and further operation of automatic control systems (ACS) for complex ship steam power facilities during the life cycle can be attributed to the direct dependence of the efficiency of control systems on the control algorithms used at the design stage, which do not allow taking into account the complexity and diversity of possible disturbing factors affecting the operation of the marine steam boiler; technological methods used in the processes of adjustment and adjustment of technical controls; terms of preventive maintenance and repair, which do not always meet the requirements due to the desire of the customer's company to minimize costs. As a rule, maintenance personnel do not have the rights and authority to repair and configure certified automation equipment that is under warranty and post-warranty service. And due to such limitations, as well as insufficient use of modern methods of identification and adaptive control in the automated control systems of ship power plants, automation tools are operated inefficiently, which in turn can lead to a decrease in the reliability and durability of equipment, to excessive fuel consumption, and an increase in the level of atmospheric pollution [3,4,5].

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The mode of operation of the ship's boiler, i.e. its steam output D (kg / h) and steam parameters P (kgf / cm^2), is determined by the power of the main engines and the steam consumption for auxiliary mechanisms and other ship needs. The main running mode is the operation of the boilers at the full design power of the main power plant of the vessel. Deviation from this mode, as a rule, leads to a decrease in the efficiency of the installation operation and an increase in the specific fuel consumption. An uneconomical mode is the boiler boost, i.e. its operation at a steam capacity 20% higher than the nominal one. At the same time, heat losses with outgoing gases from chemical underburning increase, the efficiency of the boiler decreases, the heating surfaces are contaminated and the wear of the boiler increases due to an increase in thermal and mechanical stresses in its elements.

The complexity of the process of modeling subsystems of marine boilers is associated with the specifics of their operation in different operating modes for a long time. So the dynamic properties of the superheater are determined by the dimensions of its heating surfaces, the mode of operation and the type of disturbance. A feature of the dynamic characteristics is the presence of a delay in changing the steam temperature at the outlet of the superheater after applying a disturbance at the inlet. The delay and the time constant are greater, the thicker the walls and the length of the superheater coils. Dynamic characteristics when disturbed by a change in steam temperature at the inlet to the superheater are characterized by a significant inertia. When perturbed by a change in heat absorption or steam flow, the dynamic characteristics are less inertial.

With this in mind, carrying out optimization processes to achieve high efficiency and simultaneous reduction (minimization) of harmful emissions into the atmosphere seems to be an urgent practical task.

2. Description of the object of mathematical simulation

It is known that energy efficiency is the maximum reduction in energy costs to generate a certain amount of heat. At the same time, the efficiency of a boiler plant is often shaved as the main criterion for energy efficiency. An important factor influencing the value of efficiency is the process of fuel combustion.

In most currently used fuel combustion devices, the optimization of the combustion mode is ensured by maintaining the ratio of fuel and air consumption (by changing the pressure in front of the burner) in accordance with the regime map of the steam boiler [7]. This method is not efficient enough, it does not allow keeping records of changes in air temperature and humidity, fuel calorific value and a number of other factors. In this regard, when compiling regime maps, the presence of a significant excess of air is allowed to prevent the occurrence of chemical underburning. As a result, in some modes, the amount of air exceeds the optimum by 1.5-2 times, which leads to the need to heat the excess air supplied, that is, to an increase in heat losses with gases and, as a result, to a significant decrease in boiler efficiency [8]. The existing automatic control systems (ACS) for optimizing the "fuel-air" ratio used by gas analyzers produce the process of regulation by the value of O_2 in the exhaust gases. However, these systems, as a rule, do not work in the regulation mode, and the gas analyzer is used in the monitoring mode, which is due to a number of reasons [9]:

- the concentration of O_2 in flue gases depends not only on the intensity of the blast, but also on other operating conditions (uncontrolled air leakage, changes in the characteristics of the burners during operation, non-identity of the burners in the boiler, change in the calorific value of the fuel caused by the transition from heavy to light, temperature fluctuations and humidity of the blast air, etc.), which, in turn, reduces the efficiency of the system with oxygen content control;
- limited distribution of controllers that have adaptive and stable (reliable) algorithms for working with gas analyzers (many of the developed control algorithms do not take into account transient processes in the furnace when the power changes, i.e. they do not have the property of optimizing the excess air coefficient α).

Also, according to the generally accepted method of debugging ACS with boiler parameters [10], it is recommended based on the dependence of efficiency and total losses on excess air, determined individually for each steam generator, it is advisable to maintain the excess air coefficient (α), at which the boiler efficiency η_x tends to their maximum and loss are reduced to a minimum.

3. Analysis of experimental data

The value α mainly affects q_2 (heat losses with exhaust gases) and q_3, q_4 (heat losses from chemical and mechanical fuel underburning); experimental dependences of the influence of losses on the efficiency water-tube steam boiler [11] at the values of the excess air coefficient α are shown in (Fig. 1).

The section for regulating the efficiency of the combustion process in terms of the oxygen content in the flue gases consists of a combustion chamber and a convective overheating gas duct adjacent to it to the place for measuring the O_2 content, %. The input control action of the section is the flow rate of air entering the furnace $Q_в$, and the initial (adjustable) value is the content of free oxygen in the return chamber of the gas duct behind the O_2 superheater, %. The optimal value of O_2 in the return chamber at rated load and combustion of pulverized fuel lies within 3 - 5%; when burning fuel oil and liquefied gas, it is much less (from 0.2 to 2%) [12].

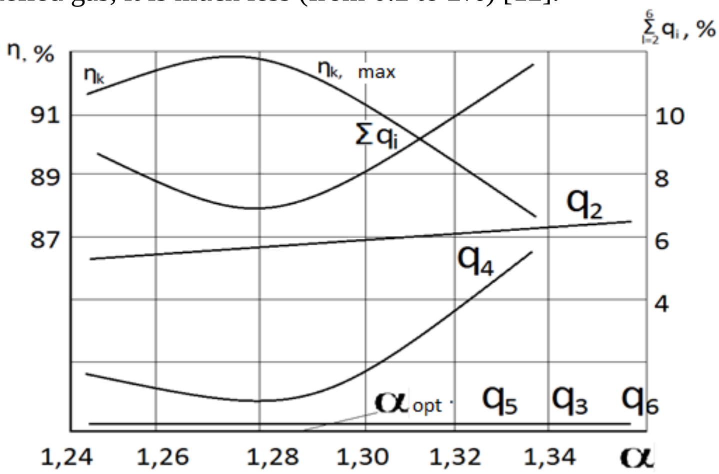

Figure 1: Experimental dependences $\sum_{i=2}^{6} q_1 = f_a$ and $\eta_к = f_a$ for a Mitsubishi MB50 steam boiler installed on tankers with a steam output of 50 t/h.

Of practical interest is the analysis of the experimental dependence [5] of the heat losses of the auxiliary boiler q_2, q_3 on the excess air coefficient α. As can be seen from the above dependence (see Fig. 1), with an increase in the value of q_2, it increases, and the loss from chemical incompleteness of combustion q_3 tends to zero.

With a further increase in α, the value of q_3 again begins to grow due to a decrease in the temperature level in the furnace. And the minimum total value (q_2 + q_3) will correspond to the optimal or economical value of α.

On fig. Figure 2 shows the experimental dependences [13] of steam capacity D, excess air coefficient α, hot air temperature $t_{gв}$, gas velocity v_{yx}, heat loss q_2 and efficiency of the auxiliary marine boiler η, obtained during heat engineering tests of a Mitsubishi MAC - 35 marine steam boiler, steam capacity 7 kg/s. which is equipped with an economizer and an air heater. An analysis of the experimental data (see Fig. 1, 2) shows that the boiler has the most economical mode of operation (50% of the nominal heat load), in which the efficiency takes on a maximum value. A photograph of a water-tube marine boiler Mitsubishi MAC - 35 is shown in fig. 3. At the same time, the task of searching for opportunities to increase the efficiency for other operating modes of the boiler plant seems to be relevant. Thus, the task of finding ways to reduce heat losses in order to increase the efficiency and energy efficiency of the boiler plant as a whole is promising.

LOAD		25%	50%	75%	100%
EVAPORATION	kg/h	8,750	17,500	26,250	35,000
DRUM PRESSURE	kg/cm^2	16.0	16.0	16.0	16.0
FEED WATER TEMP.	deg.C	80.0	80.0	80.0	80.0
SATURATED STEAM TEMP.	deg.C	203.4	203.4	203.4	203.4
BOILER EFFICIENCY (LHV BASE)	%	82.1	82.8	81.9	80.5
CALORIFIC VALUE — HHV	kcal/kg	10,280	10,280	10,280	10,280
CALORIFIC VALUE — LHV	kcal/kg	9,713	9,713	9,713	9,713
FUEL OIL CONSUMPTION	kg/h	644	1,277	1,937	2,628
EXCESS AIR RATE	%	31	16	15	15
O_2 RATE	%	5.0	3.0	2.9	2.9
COMBUSTION AIR FLOW	kg/h	11,820	20,740	31,190	42,320
FLUE GAS FLOW	kg/h	12,460	22,020	33,130	44,940
AMBIENT AIR TEMP.	deg.C	45	45	45	45

Figure 2: Operation Parameters of Mitsubishi MAC 35 Auxiliary Steam Boiler (Mode Map) [6]

Figure 3: Photograph of a Mitsubishi MAC 35 marine steam boiler [6]

4. Calculation of heat losses

The method for determining the efficiency of a steam water-tube boiler by direct balance [14] requires the creation of a complex measuring circuit for determining the flow rate and parameters of water and steam flows, which is possible only on special test benches. Under operating conditions, it is much easier to determine the heat loss q_i - based on the results of measurements of the parameters of the processes occurring in the air-gas path of the boiler. In this case, the efficiency is determined by the method of inverse heat balance [15].

In a steam boiler, the following heat losses are usually taken into account: with the initial flue gases q_2 from chemical q_3 and mechanical q_4 incomplete combustion of the fuel and to the environment q_5. Then the boiler efficiency is determined by the inverse heat balance equation according to the formula [16]:

$$\eta_\kappa = 100 - (q_2 + q_3 + q_4 + q_5), \tag{1}$$

where q_2 is heat loss with source gases; q_3 - heat losses from chemical under burning; q_4 - heat losses from mechanical incompleteness of fuel combustion; q_5 is the heat loss due to the thermal insulation material.

In turn, q_2 is determined by the formula [17]:

$$q_2 = \frac{I_{yxg} - \alpha V_B^O C_B t_B}{Q_c^н} \cdot (100 - q_4), \tag{2}$$

where I_{yxg} is the enthalpy of exhaust gases; V_B^O is the theoretical volume of air; C_B is the heat capacity of air; t_B is the air temperature; $Q_c^н$ is the heat of combustion of the fuel.

For oil-fired steam boilers, the loss of q_4 is possible due to improper maintenance, operation with excess or lack of air and poor quality of fuel oil atomization. In these cases, the loss of q_4 appears due to soot formation and coking of fuel oil. Under normal operating conditions for oil-fired boilers, there is virtually no loss of heat q_4 for all its overloads ($q_4 = 0$) [18]. Heat losses q_3 and q_4 are associated with the perfection of the fuel combustion process, therefore they are referred to as furnace losses. The heat loss to the environment due to external surfaces q_5 is mainly determined by the dimensions of the boiler, the quality of the insulation, the layout of the air ducts and the casing. With sufficient thermal insulation and its good condition, the loss q_5 depends on the mode of operation. In the case of a normal load of a modern auxiliary steam boiler, which provides for cooling the walls with air entering the furnace, usually $q_5 = 0.1$ - 0.5% [19]. In formula (1), the losses q_2 and q_3 are of interest for analysis, since they do not affect q_5. According to [20], it was found that at the optimal value of α, the efficiency of the boiler will increase due to a decrease in losses q_2 and the absence of losses q_3. When conducting operational and adjustment tests on an industrial steam boiler MAC 35 of the company Yugspetsmontazh, Odessa, the following dependence was obtained (Fig. 4).

As can be seen from the graphs (see Fig. 4), with an increase in α, the value of q_3 begins to decrease, but at the same time, losses q_2 increase. Thus, the optimal value of α will correspond to the case when the total losses $q_2 + q_3$ are minimal.

Thus, to maintain the efficiency at the maximum possible value for the most common heat load modes, the problem of optimizing α arises. Due to the fact that the values of q_3 are small compared to q_2, it is proposed that they can be neglected. It should also be taken into account that q_2, and hence the efficiency of the boiler, is influenced by air suction processes. Thus, according to [9], a decrease in the temperature of gases as a result of an excessive supply of cold air reduces the amount of heat transferred by radiation. According to the results of experiments [21], it was found that an increase in air suction into the furnace by 0.1% reduces the amount of heat transferred by radiation to 4 - 5%. And a decrease in heat absorption by radiative heating surfaces causes an overload of the following convective surfaces, and therefore the temperature of the flue gases increases.

For example, according to [22], air suction into the furnace $\Delta\alpha_t = 0.1$ - 0.2 increases the temperature of the flue gases by 4 - 8^0 C. Air suction in the boiler flue reduces the flue gas temperature in the suction zone and reduces the amount of heat transferred by surfaces heating located at the place of suction. As a result, the temperature of the flue gases increases in the heating surfaces following the flow of gases, while these processes, as a rule, are not controlled at the boiler. An increase in the temperature of the exhaust gases leads to an increase in gas losses q_2 and, consequently, to additional fuel consumption ΔB for the production of the same amount of steam.

Thus, in order to optimize the efficiency, it is also proposed to equip ACS with additional sensors (discharge in the furnace and oxygen content in the exhaust gases) to control air suction. To determine the optimal range of α values, which allow minimizing losses q_2 and significantly increasing the efficiency, a thermal calculation was made for several thermal operating modes. An example of calculating one mode of a steam boiler (65%) is presented below.

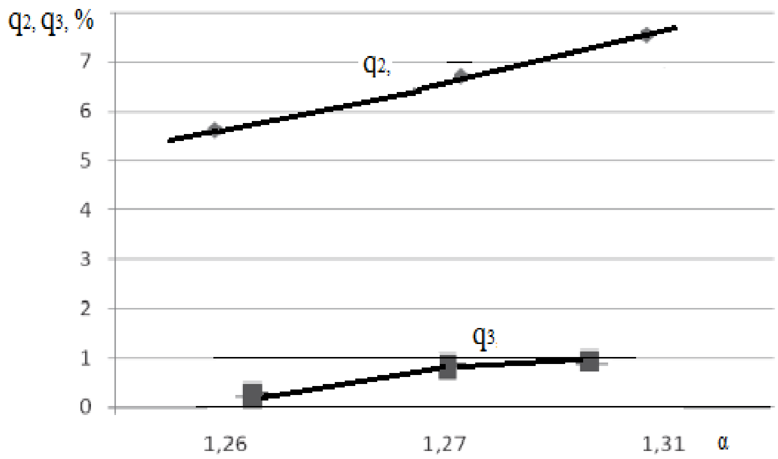

Figure 4: Experimental dependences of q2 and q3 on α (steam boiler MAC 35 when operating at a heat load of 75%)

The composition of the combustible mass (oil grade M 100) [23]:

C^G = 86,5 %; H^G = 12,6 %; N^G = 0,3 %; O^G = 0,2 %; S^G=0,4 %; A^P = 0,05 %;
W^P = 1,5 % ; $Q_c^н$ = 40800 kJ/kg.

The yield of ash (denoted as A^P) during the combustion of fuel oil does not exceed 0.1 - 0.3%. The water content (moisture content W^P) in fuel oils varies widely: from 0.5 to 5%. Watering of fuel oil occurs mainly in the process of transportation.

The composition of the working mass of fuel according to [24]:

$$C^P = C^Г \frac{100 - W^p - A^p}{100} = 85{,}16;$$
$$H^P = H^G \frac{100 - W^P - A^P}{100} = 12{,}4;$$
$$N^P = N^G \frac{100 - W^P - A^P}{100} = 0{,}29;$$
$$O^P = O^G \frac{100 - W^p - A^p}{100} = 0{,}19;$$
$$S^p = S^G \frac{100 - W^P - A^p}{100} = 0{,}39.$$

The theoretical air volume [7] is:

$V_B^O = 0{,}089 \cdot (C^P + 0{,}375 S^P) + 0{,}266 H^p - 0{,}033 O^p = 10{,}86$ m^3/kg.

Taking: I_{yxg} = 4000 kJ/kg according to flue gas diagram at flue gas temperature t_{yxg} =230 ^{0}C; t_{yxg} = 200 ^{0}C; t_B = 45 ^{0}C; t_B = 30 ^{0}C; C_B = 1,33 kJ/kg, taking into account the optimization of ACS O_2 = 2,4 %, and taking into account that then α is 1.13 according to (2) losses q_2:

$$q_2 = \frac{4000 - 1{,}13 \cdot 10{,}86 \cdot 1{,}33 \cdot 45}{40800} \cdot 100 = 8{,}0 \ \ \%.$$

Losses q_3 = 1.3% - the average value for the boiler is taken; q_5 = 0.5% - taken for an auxiliary steam boiler at a load of 50% of the nominal [25].

Then the gross efficiency factor (1) of the MAS 35 boiler:

$\eta_к$ = 100 – (8,0 +1,3+0,5) = 90,2 %.

Thus, as the calculations showed for α = 1.13, the efficiency of the boiler was 90.2%, which is 7% more than that of the operating steam boiler MAC 35, when operating at 50% of the nominal mode and at α = 1.18 (the efficiency is 82.8% (see Fig. 2)).

Taking into account the optimal value and the control system of air suction processes, the boiler efficiency increase was calculated by reducing the air suction into the furnace and flue. The assumed heat load of the boiler is 30%. The initial data for the calculation are presented in table 1.

Table 1

Initial data for calculating the increase in efficiency of the steam boiler MAC 35

Parameters	Before α optimization and without air suction control	After optimizing α and with the air suction reduction process
Exhaust gas temperature by air economizer	230	210
Excess air ratio	1,31	1,12
Flue gas losses q_2	8,0	5,2

Loss reduction q_2 for the steam boiler MAC 35 is determined by the formula [9]:

$$\Delta q = \left(\frac{\alpha_1 - \alpha_2}{\alpha_1}\right) + \left(\frac{t_1 - t_2}{t_1}\right) \times q_2,$$

where α_1 is the coefficient of excess air before the reduction of air suction (1.31); α_2 - coefficient of excess air after reduction of air suction (1.12); t_1 is the temperature of exhaust gases in the air economizer before the reduction of suction cups, 230 ^{0}C; t_2 is the temperature of exhaust gases in the air economizer after reducing suction, 210 ^{0}C; q_2 - heat loss with exhaust gases to reduce suction, 8%.

After substituting the values, we got:

$$\Delta q = 1{,}2\ \%.$$

Thus, after reducing the air suction in excess of the standard, it was possible to increase the efficiency of the steam boiler by 1.2%. It can be noted that the calculation made took into account the reduction of air suction only in the boiler flue. At the same time, subject to automatic control and further reduction of air suction in the boiler furnace, it is also possible to increase the efficiency by 1-3% [26]. Thus, the calculations showed that, taking into account the optimization and reduction of air suction, it is possible to increase the efficiency of the boiler in the steady state up to 7%.The following study was carried out for conditions when, due to the current technological process, it is impossible to reduce the heat load of the marine steam boiler on the ship, but at the same time there is a task to reduce the content of harmful emissions into the atmosphere. For the study of marine steam boilers of different steam performance, a simulation of the neural network ACS optimization α (fuel combustion mode) of the auxiliary marine steam boiler of the MAS 35 brand was carried out. The initial data for modeling and training the neural network of the neural network controller were taken from the experimental characteristics of the Mitsubishi MAS-35 SPU (Fig. 5.) [26] and the second chapter. To train the neural network controller (NNC) in the combustion control system based on experimental data [28], a training sample was compiled (Table 2). The value of the coefficient of excess air was calculated from the content of free oxygen O_2 in the gases leaving the furnace, according to the formula indicated below, taking into account the experimental characteristics of the marine steam boiler (see Fig. 5):

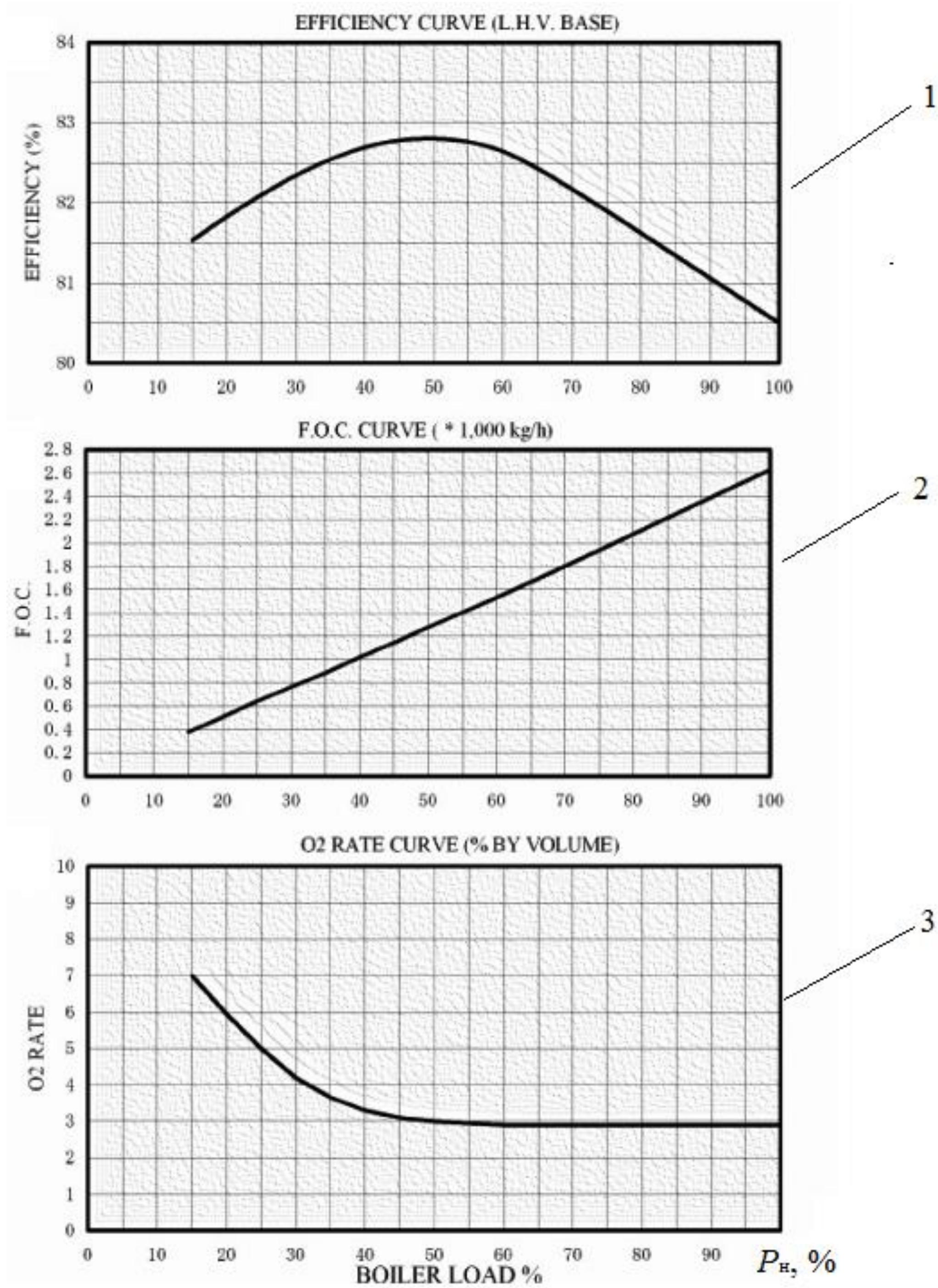

Figure 5: Experimental characteristics of dependencies: 1 – efficiency %; 2 – consumption of fuel (fuel oil) FOC; 3 – O2 content from the boiler load (Pн) of the MAC 35 ship steam generator

$$\alpha = \frac{21}{21 - O_2}$$

According to the calculations, using the method presented above, the following values obtained (see Table 2) make it possible to reduce the NO_x content to 15% compared to the traditional ACS, which does not optimize α.

Table 2
Training sample for NMC optimal fuel combustion mode according to the criterion of NOx minimization and maintenance of the maximum permissible efficiency marine steam boiler

Load, P_H %	15	30	50	70	90
α	1,32	1,22	1,15	1,10	1,05
NO_x*100 mg/m^3	1,52	1,35	2,21	4,82	6,33
efficiency, (η) %	81,5	82,3	82,8	82,1	80,5

The importance for solving the multicriteria problem of simultaneously optimizing the environmental (content of harmful emissions) and economic (efficiency) indicators of the marine steam boiler is represented by the experimental dependences shown in Fig. 6.

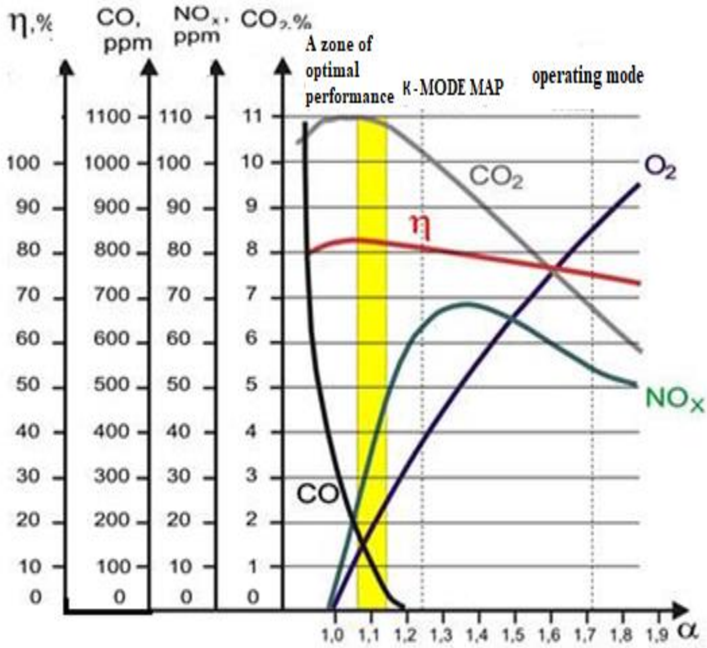

Figure 6: The influence of the coefficient of excess air on the efficiency and concentration of the main components of the smoke boiler MAC 35 with an operating pressure of 1.3 MPa and a steam consumption of 6.5 t/h

Experimental dependences demonstrate (see Fig. 6) that a decrease in α contributes to: a decrease in the content of O_2, an increase in efficiency and, as a result, a decrease in the temperature of flue gases and the consumption of electricity by the fan and smoke extractor. At the same time, the NOx values decrease, but the CO_2 content increases at the same time. The region of the economically beneficial mode of burning fuel corresponds to low values of oxygen (0.5 - 1.5%) and the content of carbon monoxide (CO) at the level of 120 - 600 mg/m^3. Work in this zone (A), highlighted in hatching, can be ensured only by automatic correction of the burners. The lines corresponding to the operation of the boiler according to the mode map (*K*) and the operating mode show when the economic performance of the boiler deteriorates due to the leakiness of the furnace-smoke tract [27].

To determine the optimal alternative, we recommend choosing the coefficient of excess air under the conditions of minimizing harmful emissions and maximizing the efficiency of the water-tube boiler MAC 35 of low thermal power, an alternative of low-power marine steam boiler. The calculation was carried out using the method of multi-criteria optimization (the main criterion with weighting coefficients).

Table 3
Data of experimental dependencies

Alternatives, α	η, %	NO_x, ppm	CO_2, ppm
0,95<α<1,2;	80	10	10,5
1,2<α<1,4;	81	62	10,3
1,4 < α < 1,6;	78	70	9,0
1,6 <α<1,8;	75	60	7,5
1,8<α<1,9.	73	50	6,0

To solve the problem of five-criteria optimization under the constraint conditions, local objective functions are defined::

(efficiency) $f_1 = 80x_1 + 81x_2 + 78x_3 + 75x_4 + 73x_5 \rightarrow \max;$
(NO_x) $f_2 = 10x_1 + 62x_2 + 70x_3 + 60x_4 + 50x_5 \rightarrow \min;$
(CO_2) $f_3 = 10{,}5x_1 + 10{,}3x_2 + 9x_3 + 7{,}5x_4 + 6x_5 \rightarrow \min.$

In this situation, the main criterion is the NOx content to be minimized. Therefore, to fulfill this condition, taking into account the imposed restrictions, the optimal solution is the minimization of α values over the entire operating range of the marine steam boiler [28].

For the task of optimizing the efficiency of the marine steam boiler, under the conditions of the given restrictions on the content of nitrogen and carbon oxides in the flue gases, the program that implements the simplex method (Fig. 7) recommends the following solutions: optimal operation plan of the marine steam boiler (maintenance of the given thermal regime taking into account the efficiency) can be written as follows: $x_1 = 0$, $x_2 = 30/417$, $x_3 = 70/834$, $x_4 = 0$, $x_5 = 0$.

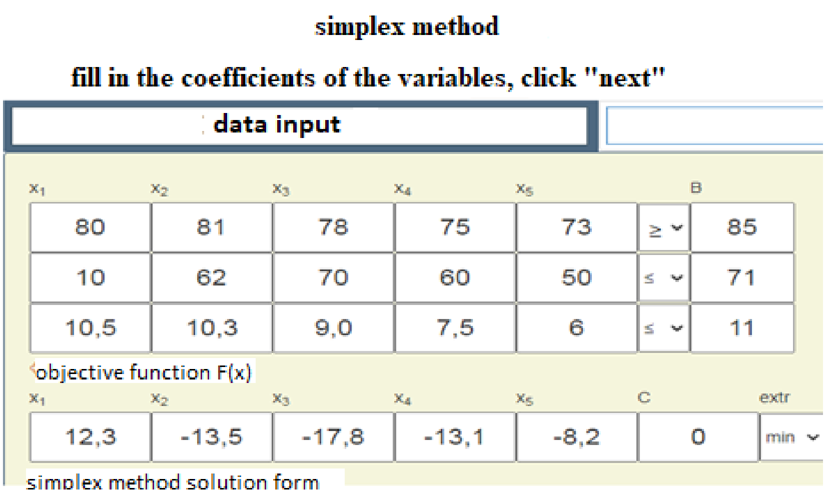

Figure 7: Program for calculating the objective function by the simplex method

5. Conclusions

Mathematical modeling of optimization processes for reducing harmful emissions into the atmosphere by the simplex method showed that:

According to the calculation made in the program (see Fig. 7), the analysis of the optimal plan of operation of the marine steam boiler under the condition of maximizing the efficiency of the marine steam boiler under the conditions of given restrictions recommends adopting the second and third strategies as the most profitable, i.e. 30% of the time in the second mode with α = 1.2 and 70% in the third thermal regime with α = 1.4, i.e. O_2 = 6%. In this case, with imposed restrictions on the content of harmful emissions in flue gases (minimization), the maximum possible efficiency of the marine steam boiler will be maintained.

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