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Reserves for Increasing the Energy Efficiency of Marine Steam Boilers

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ABSTRACT

Increasing the energy efficiency of ship power plants is one of the main issues of the modern day, which is constantly receiving considerable attention. The analysis of the economic indicators of marine steam boilers and the factors that exert a significant influence on them lead to the search for new ways of increasing their efficiency, which is an urgent task that constitutes the main goal of the work being performed. Its novelty is the substantiation of possible reserves for increasing the energy efficiency of marine steam boilers. The work summarizes the analysis of heat losses of marine steam boilers in order to determine the prospects of their reduction or beneficial use (disposal). Based on the results of the heat loss analysis, methods of increasing the energy efficiency of m steam boilers are considered. The most promising reserves for increasing the energy efficiency of steam boilers, which are promising for practical implementation, have been established.

1. Introduction.

Increasing the energy efficiency of ship power plants is one of the main issues of the modern day, which is constantly receiving considerable attention. The reasons for this are the high share of petroleum fuel consumption by the transport fleet, which is about 6% of the total volume of petroleum fuel [1]. The high cost of energy carriers constantly prompts the search for ways of its efficient use in order to minimize heat loss and prevent the harmful effects of the generated combustion products on the environment [2, 3].

Along with internal combustion engines, the largest consumers of oil fuel on a marine vessel also include marine steam boilers, as they are the most common on ships in the transport fleet. The analysis of the economic indicators of marine steam boilers and the factors that exert a significant influence on them encourage the search for new ways of increasing their efficiency, which is an urgent task that constitutes the main goal of the work being performed. Its novelty is the substantiation of possible reserves for increasing the energy efficiency of marine steam boilers.

2. Presentation of the main material

In order to determine the main methods of increasing the efficiency of steam boilers, we will write down the energy balance equation in the form of the equality of the thermal power Q_{int}, which enters the boiler and is produced in it, and the power Q_{out}, which is removed from the boiler or lost by it during operation [4 – 7]:

$$Q_{int} = Q_{out} \tag{1}$$

Next, we consider that the boiler is supplied with thermal power with heated fuel Q_f (Fig. 1), air Q_a, feed water Q_{fw}, thermal power Q_c is released from the combustion of fuel in the furnace.

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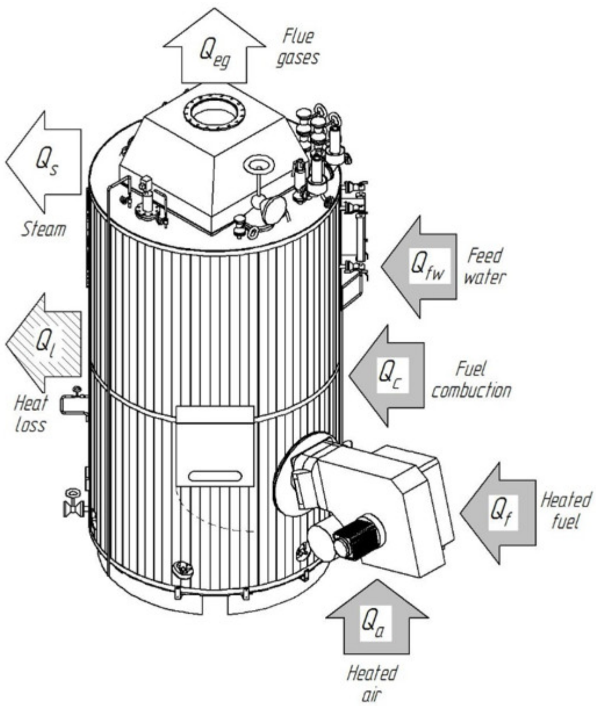
The useful thermal power of the heat carrier Q_s, the thermal power of flue gases Q_{eg} and the thermal power of losses Q_l are removed from the boiler.

Figure 1: Boiler energy balance scheme (simplified).



Source: Authors.

We write down the expression for losses (2) further, neglecting the losses due to mechanical incomplete combustion of the fuel, losses of the heat carrier due to blowing, as well as the thermal power introduced into the furnace with steam that sprays the fuel, that is, we consider the established mode of operation of the boiler most common on modern ships with mechanical nozzle:

$$Q_l = Q_{cil} + Q_{el} \tag{2}$$

where:

Q_{cil} – thermal power that is not released in the furnace as a result of chemical incomplete combustion of fuel, kW;

Q_{el} – thermal power lost through the boiler casing to the environment, kW.

The power loss Q_l usually does not exceed 5...6%, so we neglect it at this stage. Taking into account the above, equation (1) can be written in the form:

$$Q_a + Q_f + Q_{fw} + Q_c = Q_s + Qeg + Q_l \tag{3}$$

We rearrange equation (3) with respect to the thermal power Q_c in order to move on to the issues of fuel efficiency of the boiler, we obtain:

$$Q_c = [Q_s + Q_{eg}] - (Q_a + Q_f + Q_{fw}) \tag{4}$$

Since the thermal power of fuel combustion is directly related to the fuel consumption G_f (5), it can be immediately concluded from equation (4) that to increase the efficiency of the boiler, it is advisable to increase the components in round brackets and reduce the components in square brackets. Based on this, the following ways of increasing the efficiency of boilers can be distinguished:

1. Increase in thermal power Q_{fw}, introduced into the boiler with feed water;
2. An increase in the thermal power Q_f supplied to the boiler by fuel;
3. Increase in thermal capacity Q_a, introduced into the boiler by air;
4. Reduction of thermal power Q_{eg}, which is removed from the boiler with flue gases.

In order to allocate means for the implementation of the above methods of increasing the efficiency of boilers, we will give simplified expressions for calculating the components of equation (4):

$$Q_c = G_f Q_f^l \tag{5}$$

$$Q_s = D_s i_s \tag{6}$$

$$Q_{eg} = G_f I_{eg} \tag{7}$$

where:

G_f– fuel consumption per second by the boiler, kg/s;

Q_f^l– lower heat of combustion (calorific value) of fuel, kJ/kg;

D_s – steam productivity of the boiler, kg/s;

i_s – enthalpy of steam, kJ/kg;

I_{eg} – flue gas enthalpy reduced to fuel consumption.

In order to simplify the understanding of ways to increase the efficiency of boilers, expression (7) for calculating the thermal power of flue gases is presented in a simplified form (8), which contains the relationship between their consumption and temperature (at the boiler outlet) and fuel consumption by the boiler:

$$Q_{eg} = G_{eg} V_{eg} = G_f (14,3\alpha + 1) V_{eg} = G_f (14,3\alpha + 1) A_{eg} t_{eg} \tag{8}$$

where:

α – coefficient of excess air;

i_{eg} – enthalpy of flue gases related to their consumption, kJ/kg;

t_{eg} – flue gas temperature, ºC;

c_{eg} = (1,042 + 0,00028 t_{eg}) – heat capacity of flue gases, kJ/(kg×ºC);

14,3 – mass of air required for complete fuel combustion, kg/kg.

The components given in equation (3) in round brackets are calculated by expressions:

$$Q_a = G_a c_a t_a = 14,3\alpha G_f c_a t_a \tag{9}$$

$$Q_f = G_f c_f t_f \tag{10}$$

$$Q_{fw} = D_s V_{fw} = D_s c_{fw} t_{fw} \quad (11)$$

where:

c_a = 1,005...1,009 – heat capacity of air, kJ/(kg×ºC) (at temperatures ta = 50...100 ºC);

t_a – air temperature, ºC;

t_f – fuel temperature, ºC;

c_f = (1,738 + 0,00251 t_f) – fuel heat capacity, kJ/(kg×ºC);

i_{fw} – enthalpy of feed water, kJ/kg;

t_{fw} – feed water temperature, ºC;

t_{fw} = 4,2 kJ/(kg×ºC) – heat capacity of feed water.

By substituting expressions (5), (6), (8)...(11) into equation (4), and carrying out its transformation with respect to fuel consumption, we will obtain an expression for the approximate calculation of hourly fuel consumption by the boiler:

$$G_f = \frac{D_s(i_s - c_{fw}t_{fw})}{Q_f^l + c_f t_f + 14,3\alpha c_a t_a - (14,3\alpha + 1)\, C_{eg} t_{eg}} \quad (12)$$

Thus, analyzing the last equation, it can be stated that the given methods of increasing the efficiency of the boiler can be implemented by the following means:

- by heating the feed water (method 1), which ensures an increase in the temperature of t_{fw} and a decrease due to this numerator of expression (12), which is adequate to an increase in Q_{fw} (4) and results in a decrease in the need to introduce heat into the fuel-fired boiler and a reduction due to this expenses G_f;

- by heating the fuel (method 2), which ensures an increase in its temperature t_f and an increase due to this denominator of expression (12), which is adequate to an increase in Q_f (4) and results in a decrease in the need to introduce heat into the boiler with fuel and a reduction due to this expenses G_f;

- by heating the air (method 3), which ensures an increase in the temperature t_a and an increase due to this denominator of expression (12), which is adequate to an increase in Q_a (4) and results in a decrease in the need to introduce heat into the fuel-fired boiler and, due to this, a reduction in its consumption G_f;

- by increasing the efficiency of heat use in the boiler (method 4), which ensures a decrease in the temperature t_{eg} of flue gases at its exit and an increase due to this denominator of expression (12), which is adequate to reduce Q_{eg} (4) and results in a decrease in the need for heat input to the boiler with fuel and thereby reducing its consumption G_f.

In order to illustrate the reserves of each of the above methods of increasing efficiency, we will calculate the fuel consumption of the Aalborg Mission OL auxiliary boiler according to expression (12).

Steam productivity of this boiler D_s = 25000 kg/h, steam pressure p_s = 1,6 MPa (steam saturation temperature t_s = 201,37 ºC), its enthalpy i_s = 2792.2 kJ/kg; fuel RMG 180, Q_f^l = 40200 kJ/kg. We take the following temperatures as variables: feed water t_{fw} = 60...110 ºC; fuel t_f = 120...145 ºC; air t_a = 45...95 ºC; flue gases t_{eg} = 450...200 ºC; and the coefficient of excess air α = 1,05...1,55. We consider the basic regime with the following parameter values: t_{fw} = 60 ºC; t_f = 120 ºC; t_a = 45 ºC; t_{eg} = 420 ºC; α = 1,15, which according to expression (12) gives the hourly fuel consumption of the boiler G_f = 1942,3 kg/h (it is interesting to note that the manufacturing company gives the fuel consumption value for this boiler at the level of 1900 kg/h, which illustrates the functionality expression (12)). The results of the calculations are illustrated in fig. 2...fig. 7 and summarized in table. 1.

The data constructed in fig. 2...fig. 7 graphs and tables 1 testify to the following:

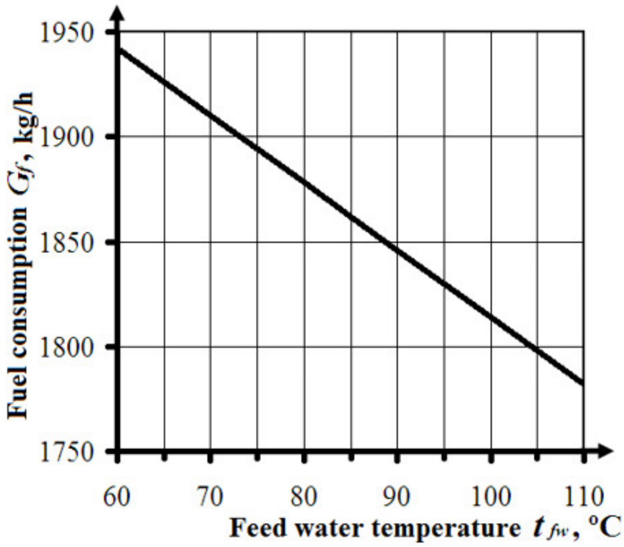
Method 1 (Fig. 2) due to increasing the temperature of the feed water t_{fw} from 60 to 110 º? can provide a fuel saving of ΔG_f = 160 kg/h (or about 9%) compared to the basic mode. The method can be implemented by heating the feed water with waste heat in special heat exchange devices - economizers. In principle, it is possible to heat the water up to the temperature t_{fw} by 15...20 ºC lower than the saturation temperature of the steam t_s, in order to exclude the boiling of the feed water in the economizer. The method is used in ship power plants with the use of internal and external waste heat utilization of energy-generating elements (boilers themselves or diesel engines operating in parallel with boilers).

Table 1: Content and analysis of reserves of ways to increase the efficiency of shipboard steam boilers (on the example of the autonomous Aalborg Mission OL boiler).

No. method	Content of the method	Means of implementation of the method	Device for implementing the method	Efficiency of the method (reduction of fuel consumption, ΔG_f)
1	Increase in thermal capacity Q_{fw}, introduced into the boiler by feed water	Feed water heating (t_{fw} increase)	Economizer	160 kg/h, an efficient method, is used in marine boiler plants
2	Increase in thermal capacity Q_f, which is introduced into the boiler by fuel	Fuel heating (t_f increase)	Fuel heater	4 kg/h, an inefficient method
3	An increase in the thermal power Q_a introduced into the boiler by air	Air heating (increasing t_a)	Air heater	48 kg/h, the method is effective at high steam productivity (used mainly in stationary boiler plants)
4	Reduction of thermal power Q_{eg}, which is removed from the boiler with flue gases	A decrease in the temperature of flue gases t_{eg}	194 kg/h, an effective method, is used in boilers operating with a load close to constant, where the temperature t_{eg} of the flue gases at the boiler exit below the dew point temperature t_p is excluded. Requires a significant increase in the size of the boiler.	

Source: Authors.

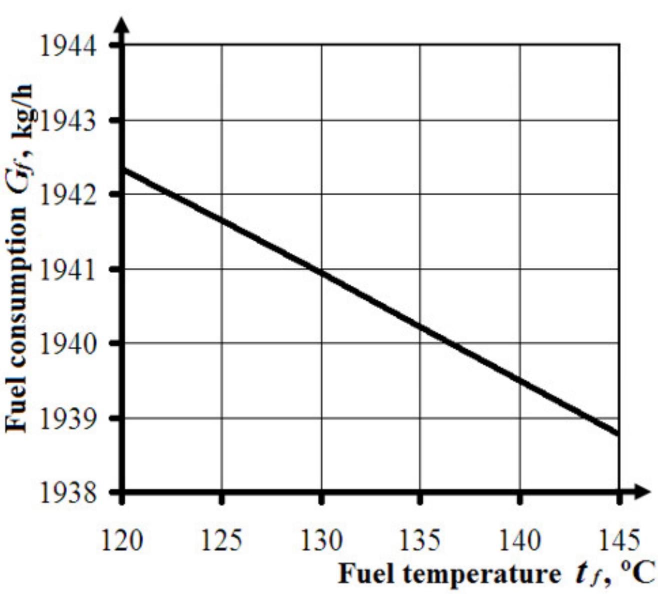
Figure 2: Dependence of fuel consumption on feed water temperature.



Source: Authors.

Method 2 (Fig. 3) by increasing the fuel temperature t_f from 120 to 145 ºC (within the limits of the fuel viscosity allowed by the manufacturer for the combustion device) can provide fuel savings of ΔG_f = 4 kg/h (or about 0,25%). The method for auxiliary boilers is inefficient.

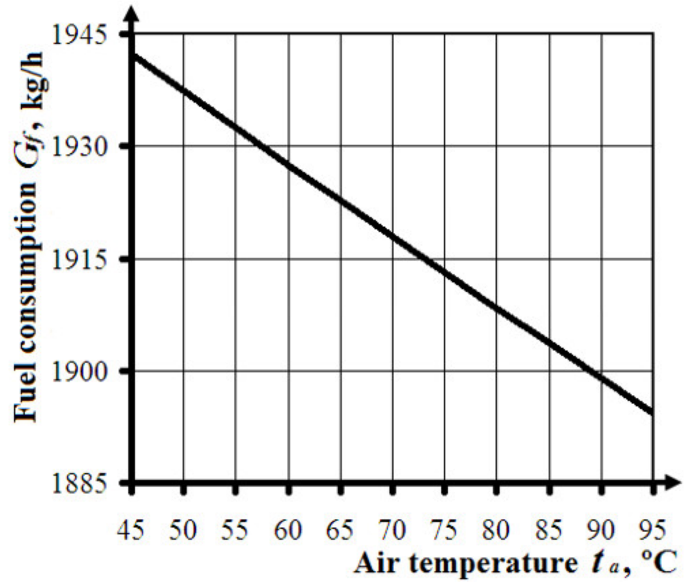
Figure 3: Dependence of fuel consumption on fuel temperature.



Source: Authors.

Method 3 (Fig. 4) due to increasing the air temperature t_a from 45 to 95 ºC can provide fuel savings ΔG_f = 48 kg/h (or about 3%). The method for marine auxiliary boiler plants is inefficient, it is used in air supply systems of marine main and stationary boiler plants, in particular at thermal power plants with large steam productivity and air consumption due to the use of air heaters.

Figure 4: Dependence of fuel consumption on air temperature.



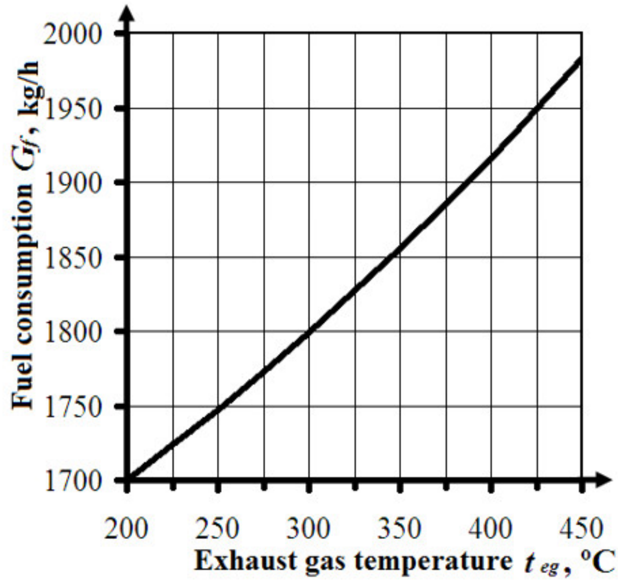
Source: Authors.

Method 4 (Fig. 5) by reducing the temperature of the flue gases at the boiler exit from 450 to 200 ºC can save fuel ΔG_f = 194 kg/h (or about 10%). Lowering the temperature of the exhaust gases at the boiler outlet requires constructive provision of a more complete use of heat in the boiler furnace. Approaching the temperature of the exhaust gases t_{eg} to the temperature t_p of the dew point when implementing this method has its own danger of precipitation of dew and low-temperature corrosion of the heat exchange surfaces and gas ducts, in particular when working at partial load, therefore method 4 is used for boilers operating with a constant load, mainly in stationary boiler plants [8, 9].

In fig. 6 shows a diagram of the distribution of fuel economy reserves by the methods discussed above. This diagram clearly illustrates the most promising ways to increase the energy efficiency of ship's steam boilers, in comparison with all the considered ones.

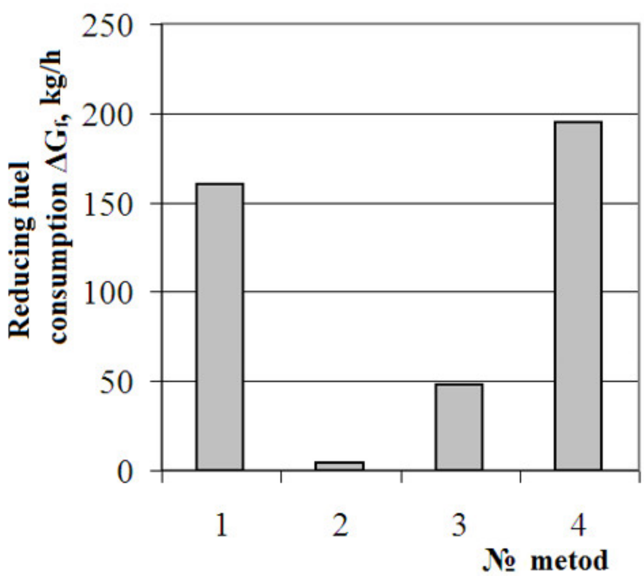
The graph in fig. 7 shows the influence of the coefficient of excess air on the fuel consumption of the boiler. The lowest fuel consumption occurs at α = 1,05 (G_f = 1905,5 kg/h), however, such low coefficients of excess air in operation lead to smoking of the furnace and activation of photocells of the protection system, therefore manufacturers recommend maintaining the coefficient of excess air at the level of α = 1,15. From the graph in fig. 7, it is clear that with an increase in α, the efficiency of the boiler decreases, this is explained by an increase in the content of unused air in the flue gases, which is heated in the furnace and removes useful heat from it (at α = 1,15, about 15% of the air is not used in the furnace, and at α = 1,55 for 40% more). Thus, for the Aalborg Mission OL boiler, increasing α from 1,15 to 1,55 increases fuel consumption from 1905 kg/h to 2105 kg/h (by 200 kg/h or 10%).

Figure 5: Dependence of fuel consumption on the temperature of the exhaust gases.



Source: Authors.

Figure 6: Diagram of the distribution of fuel economy reserves by methods.

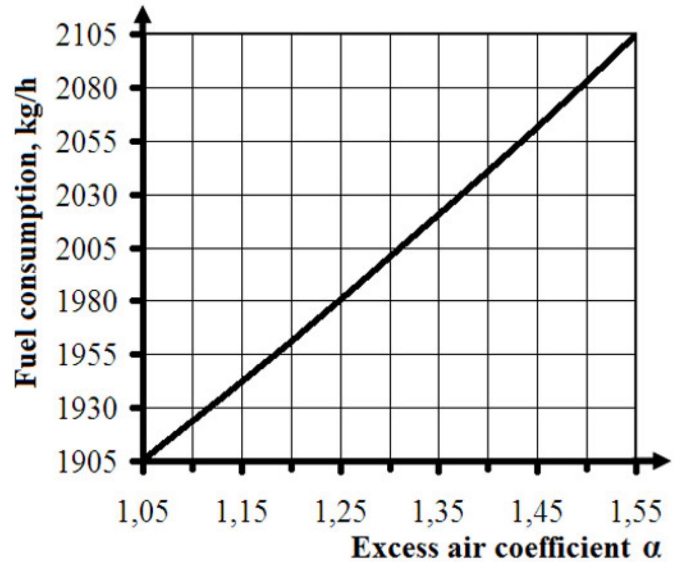


Source: Authors.

Conclusions.

1. The analysis of heat losses of shipboard steam boilers is summarized in order to determine the prospects for their reduction or beneficial use (disposal).
2. Based on the results of the performed heat loss analysis, methods of increasing the energy efficiency of marine steam boilers are considered.

Figure 7: Dependence of fuel consumption on the excess air coefficient.



Source: Authors.

3. Among the researched reserves for increasing the energy efficiency of steam boilers, it was established that the following are the most promising for practical implementation:
   - due to the increase in thermal power Q_{fw}, which is introduced into the boiler with feed water;
   - due to the reduction of the thermal power Q_{eg}, which is removed from the boiler with flue gases.
4. In order to implement the proposed most effective methods of increasing the energy efficiency of steam boilers, further research into the most optimal equipment that will meet the requirements is necessary.

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