Increase of efficiency and reliability of liquid fuel combustion in small-sized boilers

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Abstract. One of the ways to increase the efficiency of using fuels is to create highly efficient domestic energy equipment, in particular small-sized hot-water boilers in autonomous heating systems. Increasing the efficiency of the boiler requires a reduction in the temperature of the flue gases leaving, which, in turn, can be achieved by installing additional heating surfaces. The purpose of this work was to determine the principal design solutions and to develop a draft design for a high-efficiency 3-MW hot-water boiler using crude oil as its main fuel. Ensuring a high efficiency of the boiler is realized through the use of an external remote economizer, which makes it possible to reduce the dimensions of the boiler, facilitate the layout of equipment in a limited size block-modular boiler house and virtually eliminate low-temperature corrosion of boiler heat exchange surfaces. In the article the variants of execution of the water boiler and remote economizer are considered and the preliminary design calculations of the remote economizer for various schemes of the boiler layout in the Boiler Designer software package are made. Based on the results of the studies, a scheme was chosen with a three-way boiler and a two-way remote economizer. The design of a three-way fire tube hot water boiler and an external economizer with an internal arrangement of the collectors, providing for its location above the boiler in a block-modular boiler house and providing access for servicing both a remote economizer and a hot water boiler, is proposed. Its mass-dimensional and design parameters are determined. In the software package Boiler Designer thermal, hydraulic and aerodynamic calculations of the developed fire tube boiler have been performed. Optimization of the boiler design was performed, providing the required 94% efficiency value for crude oil combustion. The description of the developed flue and fire-tube hot water boiler and the value of the main design and technical and economic parameters are given.

1. Introduction

One of the main ways to improve the efficiency of fuel use is the development and creation of highly efficient energy equipment. Presently on the market, small-capacity boilers (0.1-4 MW) have an efficiency of 90-92% in the combustion of natural gas and diesel fuel and are generally not designed for burning sulfur-containing fuels (mazut, crude oil). The boilers running on fuel oil have an efficiency of only 87-90%, which is explained by the need to maintain a high temperature of the exhaust gases to 250 °C to reduce the intensity of low-temperature sulfur corrosion of the tail heating surfaces. PJSC "Transneft" operates a large number of fire-tube boilers that operate on crude oil at their subordinate facilities. The purpose of this work was the development of a 3 MW hot-water boiler using crude oil for block-modular boiler houses (BMBH). The initial technical requirements for the boilers under development are given in Table 1.
### Table 1. Technical characteristics of the boiler

| Name of the characteristic                        | Unit of measurement | Value      |
|--------------------------------------------------|---------------------|------------|
| Heating capacity                                 | MW                  | 3          |
| Water temperature at the boiler inlet            | °C                  | 70         |
| Water temperature at the boiler outlet           | °C                  | 95         |
| Water flow through the boiler                    | T/h                 | 103,2      |
| Calculated (excess) water pressure at the boiler inlet | MPa             | 0,7        |
| Air excess coefficient                           | --                  | 1,15       |
| Overall dimensions (LxWxH) without taking into account the burner device and additional energy-efficient equipment, not more than | Mm                  | 4765x2170x2450 |
| Values of gross boiler efficiency at nominal parameters | %                  | 94,2       |

As a hot water boiler for BMBH, it was decided to use a fire tube boiler, which is most often used as sources of low and medium power heat generation. The main advantages of fire-tube boilers are:
- compactness of the boiler, which allows for a small size to provide high thermal power;
- simplicity of design, reducing the capital cost of production;
- gas-tightness, which ensures operation under supercharging without a smoke exhauster;
- low hydraulic resistance, which reduces operating costs;
- thermal inertia due to the large volume of using water, which allows maintaining a stable temperature at the outlet.

### 2 Main approaches

When designing the boiler, a special requirement was made to increase the efficiency of fuel use, since the efficiency of the developed boiler should not be less than 94% when burning crude oil. Obviously, ensuring such an efficiency is not in itself a technical problem. However, in this case the problem was solved under conditions of two serious limitations. The first of these is the dimensions of the boiler, which, together with the auxiliary equipment, should be placed in a limited size in a block-modular boiler house (BMBH). The second limitation is related to ensuring reliable long-term operation of the boiler in conditions of low-temperature sulphur corrosion of cold heating surfaces that occurs when burning sulfuric oil.

The temperature of the outgoing flue gases behind the boiler is determined by the required value of the gross boiler efficiency $\eta$, which depends on the heat loss with outgoing gases $q_2$, heat losses from chemical underfire $q_3$ and from external cooling $q_5$.

According to [1], the concentration of CO in the flue gas leaving should not be 160 mg/m$^3$ when burning crude oil (in terms of dry gases, $\alpha = 1$, normal physical conditions), which corresponds to the values of $q_3 = 0.03$-$0.05$ %. The loss of heat from external cooling was assumed to be $q_3 = 0.28\%$ similar to serially produced boilers. The amount of heat loss with flue gases $q_2$ depends on the fuel properties, the temperature of the exhaust gases and the excess air factor $\alpha$ in the flue gases. With the value of $\eta = 94.2\%$ in the calculations, the flue gas temperature was 144°C.

Low-temperature sulfur corrosion of the heating tail surfaces is determined by the temperature of the dew point of water vapor and sulfuric acid vapor. The temperature of the dew point of water vapor, determined according to [2] from the value of the partial pressure of water vapor in the products of combustion of crude oil at a given value of the excess air coefficient, was 49.4°C. In turn, the temperature of the dew point of sulfuric acid vapors when burning crude oil with a sulfur content of 2.9% was determined in accordance with [3] and amounted to 148°C.
To increase the efficiency of the boiler under these conditions, it is possible in principle to install an air heater, install an additional heat exchange surface, or install a condensing heat recovery unit. The use of an air heater or condensation heat exchanger on this boiler is not possible due to the limited size of the block modular boiler house and their high cost. An increase in the heat exchange surface in the boiler, which will provide the necessary temperature of the exhaust gases 144°C, will lead to an increase in the dimensions of the boiler in excess of the established dimensional constraints (see Table 1) and the high corrosion rate of the metal pipes. The use of acid-resistant materials for the tail heating surfaces will significantly increase the cost of the boiler and therefore is impractical.

In this regard, in order to ensure a high efficiency of the boiler, it was decided to use the pre-installed remote economizer, which allows raising the temperature of the combustion products behind the boiler to 300-350°C, reducing the dimensions of the boiler and virtually eliminating the low-temperature corrosion of the heat exchange surfaces located in the boiler body. Remote economizer will reduce the cost of maintenance and replacement of elements exposed to corrosion, as well as simplify the layout of equipment in a block-modular boiler house (BMBH).

3. Construction of the fired boiler

Based on the design experience, it is possible to use a two-way and three-way (by gas) schemes of a flame tube hot water boiler. Considering the conditions for the layout of the boiler and the remote economizer in the BMBH (the output of gases from the remote economizer is oriented to the chimney), three options for the layout of the equipment were considered at the design stage: a two-way boiler and a one-way remote economizer (layout "2-1"), a two-way boiler and a three-way remote economizer (layout "2-3") and a three-way boiler and a two-way remote economizer (layout "3-2").

Preliminary constructive calculations of these layout options were performed in the "Boiler Designer" software package. The results of calculations showed that the most optimal is the layout of "3-2" (Figure 1), because it has less hydraulic resistance and acceptable aerodynamic resistance, which allows the use of commercially available burners [4].

![Figure 1](image_url)

**Figure 1.** Scheme of layout "3-2": 1 – water inlet; 2 – remote economizer; 3 – main body of boiler; 4 – water outlet.
When developing the design of the fire tube boiler, the scheme was adopted with a symmetrical distribution of the smoke tubes of the second and third gas pass relative to the axis of the flame tube. Figure 2 shows the layout of the main body of the fire tube boiler. The flange 1, the door 15, the cylindrical part of the boiler body 6 and the outlet chamber 5 form the main body of the fire tube, inside which the fire tube 2, the bypass ducts 3 and 4, the fire tubes 7 and 8 are provided. For the rigidity of the elliptical bottoms, the embedded pipes 16 are provided.

![Figure 2. Fire-tube hot water boiler.](image-url)
The combustion of crude oil takes place in an air burner that is attached to the flange 1. The furnace of the boiler is confined to the flame tube 2 and the first bypass box 3. The combustion products after the flame tube enter the first bypass 3 and then in fire tubes of the first pass 7. After it, the flue gases enter the second transfer box 4 and from there are distributed through the smoke tubes of the second pass 8 and then collected in the outlet chamber 5.

After cooling the combustion products in the body of the fired boiler to 280°C, they through the bypass flue 14 are sent to the housing of the remote economizer.

As practice shows, the combustion of liquid fuel is accompanied by the presence of deposits on the inner wall of the smoke tubes. The choice of two passes of smoke tubes in the main body of the boiler was made from the condition of keeping the velocity of combustion products in them in the range of 20-25 m/s in order to improve the convective heat transfer. At the same time, the diameter of the smoke tubes, equal to 76 mm, was chosen as the optimal one. Using larger diameter pipes allows to reduce the intensity of deposits on the inner wall of the pipe and to simplify their cleaning. The adopted dimensions of the flame tube are provided according to the thermal calculations, the temperature at the outlet of the flame tube is about 1100°C at the rated load. This makes it possible to ensure reliable operation of the boiler even with a high sulfur content in the fuel.

The boiler is equipped with lugs 11 for transporting it, as well as a support 13. For implementation of various operational activities, the boiler is equipped with a manhole 12 and doors 15 on the front of the boiler. A choke 17 is provided for draining the boiler, as well as for purging.

4. The design of the remote economizer

The remote economizer (figure 3) on the gas side is divided by the plate into two passes, going through which combustion products through the flue gas flue are diverted into the chimney. During the development process, it was taken into account that the remote economizer should be located above the boiler in the BMBH and provide access to both the remote economizer and the hot water boiler (Figure 4). The size restriction of the remote economizer led to the use of a dense tube bundle and a high resistance along the combustion products path.

![Figure 3](image.png)

Figure 3. Scheme of the remote economizer: 1 - the branch pipe of the combustion products inlet, 2 - the body, 3 - the heat exchange surface, 4 - the collectors, 5 - a dividing partition, 6 - exit of combustion products.
Based on the results of thermal and hydraulic calculations by the “Boiler Designer” software package, pipes with an external diameter of 38 mm and a wall thickness of 3 mm were chosen for the heat exchanger surface of the economizer. The use of pipes with a smaller diameter significantly increases the likelihood of cross-section drift by deposits, and the use of pipes with a larger diameter will substantially increase the dimensions of the heat exchange surface. The number of pipes connected in parallel (24 pipes) was determined from the condition of ensuring a mass water velocity in the pipes of not less than 1200 kg/(m² × s), to prevent the horizontal pipes from introducing sediments [5].

**Figure 4.** Sketch of fire-tube boiler with remote economizer.

Comparison of the two versions of the housing of the remote economizer: with the external and internal arrangement of the collectors showed the advantage of the latter option (Figure 3). In this case, a good gas-tight housing of the remote economizer is ensured and an additional heat sink is provided.

The water supply with a temperature of 70°C is carried to the input of the remote economizer, after heating in which it passes through the bypass 9 (Figure 2) into the water volume of the fire tube boiler. After heating in the fired boiler, the water with the required temperature of 95°C is discharged through the outlet pipe 10.

The design parameters and results of calculating the fire tube boiler for the operating range of the loads are given in Table 2.
### Table 2. Design parameters and results of calculating the fire tube boiler

| Parameters                                | Unit of measurement | Value       |
|-------------------------------------------|---------------------|-------------|
| **Constructive parameters**               |                     |             |
| *The main body of the fire tube boiler:*  |                     |             |
| Boiler overall dimensions                  | Mm                  | 4552x2150x2300 |
| Weight of the metal of the boiler without regard to supports and remote economizer | Kg                  | 8930        |
| **Remote economizer:**                    |                     |             |
| Overall dimensions (LxWxH)                | Mm                  | 3812x812x1605 |
| Weight of the remote economizer           | Kg                  | 1831        |
| Number of pipes connected in parallel     | -                   | 24          |
| Number of tubes in a row                  | -                   | 12          |
| Number of rows of pipes                   | -                   | 40          |
| **Mode parameters:**                      |                     |             |
| Load (from nominal)                       | %                   | 100         |
| Fuel consumption (crude oil)              | T/h                 | 0,2873      |
| Air excess coefficient                    | -                   | 1,15        |
| Boiler thermal output                     | KW                  | 3008        |
| Boiler thermal output %                   | %                   | 94,8        |
| **Gas temperature:**                      |                     |             |
| At the outlet from the boiler              | °C                  | 280         |
| At the output of the remote economizer    | °C                  | 131         |
| **Water temperature:**                    |                     |             |
| At the entrance to the boiler              | °C                  | 70          |
| At the output of the remote economizer    | °C                  | 71,8        |
| At the outlet from the boiler              | °C                  | 95          |

### Conclusion
1. The thermal scheme of the "three-way boiler and two-way economizer" has been determined as the optimal layout of the hot-water boiler with the remote economizer.
2. A design is proposed and thermohydraulic and aerodynamic calculations of a 3 MW fire tube boiler operating on crude oil with a remote economizer for a block-modular boiler house are performed.
3. It is shown that the design of the remote economizer with the internal location of the collectors in terms of design and operational characteristics is preferable to the external arrangement of the collectors.

### References
[1] GOST 30735-2001 Heating water heating boilers with heating capacity from 0.1 to 4.0 MW. General specifications.
[2] Thermal calculation of boilers (normative method). - SPb: NPO CKTI, 1998.
[3] RD 34.26.105. Methodical instructions for preventing low-temperature corrosion of heating surfaces and flue gas of boilers.
[4] Development of energy-efficient solutions for a small-size hot-water boiler/Roslyakov PV, Proskurin Yu.V., Ionkin IL, Sterkhov K.V.//Industrial Energy, 2017. №3. Pp. 25-32.

[5] Steam-fired boilers for power plants and boiler-houses/EF Buznikov, A.A. Veres, V.B. Mushrooms. - Moscow: Energoatomizdat, 1989.