Autonomous Energy-Efficient Complexes Based on Crude Oil for Working in Arctic Conditions

P V Roslyakov¹, Yu V Proskurin², B G Grisha² and I L Ionkin¹

¹National Research University "MPEI", Moscow, Russia
²PJSC "Transneft", Moscow, Russia

Abstract. The work is devoted to solving scientific and technical problems on the development of new generation Russian power equipment. Comprehensive theoretical and experimental studies of the effect of aerodynamic and heat-mass exchange processes on the ignition and combustion of crude oil in the straitened conditions of fire-tube boilers are reviewed and described. Based on the results of the research, design developments were carried out, prototypes of a fire-tube hot-water boiler with a remoted economizer and an automated low-emission burner device were manufactured and successfully tested. The efficiency of the boiler more than 94% and the reduced level of pollutants emissions in the operating load range are confirmed.

1. Introduction
Reliable heat supply to the population and industrial facilities has a huge impact on the social and economic condition of Russia. The importance of heat supply is especially strong in the cold season, when the country's vital activity essentially depends on it. According to the average long-term data, the duration of the heating period in Russia ranges from 22-25 weeks in the south to 40-45 weeks or more in the north [1]. In this regard, it is particularly important to ensure uninterrupted heat supply to industrial facilities and settlements in hard-to-reach areas of the Far North and the Arctic. Often in such areas there is a shortage of traditional energy fuels (coal, fuel oil) and their provision is due to delivery in a short summer period. One of the promising options for energy supply in this case is the using of crude oil as fuel, the deposits of which are located in the immediate vicinity. In this regard, the task of creating and developing modern domestic autonomous high-efficiency and environmentally friendly energy complexes running on crude oil is very urgent.

2. Main approaches
To effectively solve this problem, the National Research University "MPEI" and PJSC "Transneft" have developed and created mobile autonomous complexes as part of block-modular boiler houses (BMBH). These complexes include hot water boilers with a capacity of 0.5 to 3.0 MW of increased efficiency of at least 94%, burning untreated crude oil in low-emission burners with a reduced yield of nitrogen oxides NOₓ and carbon monoxide CO.

To solve the problems of ensuring high efficiency and effective protection of the boiler from low-temperature sulphur corrosion in the limited overall dimensions of the BMBH, for the first time for boilers using crude oil as fuel, it was proposed to use a pre-connected (by water) remoted economizer installed above the boiler.
According to the results of heat calculations, in order to ensure the boiler efficiency of at least 94%, the temperature of the exhaust gases at the nominal heat output should be no more than 140°C. This value is significantly lower than the same indicator for existing hot water boilers.

Usually during burning liquid fuels in boilers the temperature of the exhaust gases is 250-300°C in order to avoid low-temperature corrosion. At the same time, a decrease in the temperature of the exhaust gases as a result of a decrease in the temperature head leads to an increase in the heat exchange surface and, consequently, the dimensions of the boiler.

For a comprehensive solution to these problems, it was decided to use a pre-connected (by water) remoted economizer in the fire-tube boiler design, the optimal connection scheme and design of which were studied in [2, 3] (Figure 1). This made it possible to increase the temperature of the combustion products behind the boiler to 300-350 °C while reducing the temperature of the gases leaving the economizer to 140°C. It was allowed to reduce the dimensions of the boiler and eliminate low-temperature corrosion of the heat exchange surfaces located in the boiler body [4, 5].

The compact remoted economizer using reduces the cost of maintenance and replacement of elements that are subject to corrosion, as well as simplify the layout of equipment in the limited dimensions of the BMBH [6-10].

3. Results

At all stages of the design of the fire-tube boiler and the low-emission burner device developed for it, complex computational studies were carried out in order to optimize the taken technical solutions. All thermal-hydraulic calculations were performed in the Boiler Designer software package, which allows using both foreign calculation methods and domestic regulatory methods. Modelling of gas-dynamic processes of ignition, burning and heat and mass transfer was carried out in the ANSYS CFX software environment [8].

The methods of thermal calculation of the furnace used in the Boiler Designer program are mainly intended for power boilers and take into account only radiation heat transfer. At the same time, recent studies have shown that a significant proportion of convective heat perception occurs in the straitened furnaces of fire-tube boilers [9]. Therefore, the results of field tests of a fire-tube hot water boiler were used for the development of computer models of fire-tube hot water boilers. More correct values of the coefficients of thermal efficiency for the furnace and convective heating surfaces of the fire-tube boiler were determined based on results of these tests and design studies.
As a result, a computer model was developed, which was used in the design of a new hot-water fire-tube boiler with a thermal capacity of 3.0 MW (Figure 2), designed for burning crude oil, diesel fuel and natural gas.

![Figure 2. 3D-model of the developed boiler](image)

(1-end-face wall for the burner installation, 2-heat pipe, 3-first turning chamber, 4-second turning chamber, 5-assembly chamber, 6-boiler body, 7-first convective heating surface, 8-second convective heating surface, 9-connecting pipe, 10-outlet pipe, 11-eye, 12-repair manhole, 13-mounting support, 14-connecting flue, 15-sashes, 16-spacing elements, 17-drain).

Based on the results of CFD modelling of the combustion process in the fire tube, the optimal values of its internal diameter and length were determined, ensuring complete combustion of all the fuels under consideration and the corresponding permissible gas temperatures for them. Based on the results of
modelling of heat and mass transfer processes into the heating surfaces, the boiler design was optimized by selecting the number and size of smoke pipes and selecting one of the possible principal designs of the remote heat exchanger. Technical and economic characteristics of the boiler are given in Table 1.

| Parameters                                               | Sign | Dimension | Value   |
|----------------------------------------------------------|------|-----------|---------|
| Overall dimensions of the main boiler body               | L×W×H| mm        | 4726×1582×2299 |
| The weight of the boiler metal excluding the supports and the remote economizer | G м | kg        | 2543    |
| Specific metal consumption taking into account the remote economizer | G м | Kg/MW    | 1458    |
| Length of welds (without economizer)                     | L w  | m         | 1400    |
| The aerodynamic resistance of the boiler, taking into account the remote economizer | Δp a | Pa       | 764-814 |
| Hydraulic resistance of the boiler taking into account the remote economizer | Δp  | MPa      | 0,1     |
| Exhaust gas temperature (oil/gas / diesel)              | θ ex | °C       | 131/133/131 |
| The gross efficiency of the boiler, taking into account the installation of a remote economizer (oil/gas/ diesel fuel) | η  | %        | 94,9/94,5/94,9 |
| Crude oil consumption                                   | B oil | kg/h    | 286,8   |
| Natural gas consumption                                 | B г | nm³/h    | 308,3   |
| Diesel fuel consumption                                 | B д | kg/h     | 267,5   |

It was used a schematic diagram with a two-pass remote economizer taking into account the layout conditions of the boiler and the remote economizer inside the BMBH (Figure 3). The gas path of the remote economizer is divided into two passes by a separating partition. The combustion products in the turning chamber, located at the end of the remote economizer near the front of the boiler, perform a U-turn and move in the direction of the rear part of the boiler. Then they are discharged through the flue to the outside into the chimney.

Figure 3. Diagram of the remote economizer: 1 – inlet of combustion products, 2-housing, 3-heat exchange surface, 4-water collectors, 5-separating partition, 6 – outlet of combustion products.
Pipes with an outer diameter of 38 mm and a wall thickness of 3 mm were selected for the heat exchange surface of the economizer. The using of pipes with a smaller diameter significantly increases the probability of skidding of the passage section by deposits. On the contrary, the using of pipes with a larger diameter will significantly increase the dimensions of the heat exchange surface. The number of pipes connected in parallel was determined from the condition that the mass velocity of water in the pipes was not less than 1200 kg/(m²·s). It is the minimum value permissible for preventing the pipes from skidding by sediments.

To optimize the economizer design numerical studies were carried out on the effect of the flue design on its aerodynamic drag in order to ensure structural simplicity execution and the absence of non-stationary effects in the flow. The proposed version of the economizer flue design allowed not only to provide minimal aerodynamic resistance, but also effective streamlining of the heating surfaces without loss of flow stability (Fig. 4).

![Figure 4. Distribution of the total pressure (Pa) with superimposed velocity vectors at a load of 100% (a) and 40% (b) of the nominal load.](image)

Fuel efficiency and environmental safety of boilers are largely determined by the burner devices. Therefore, simultaneously with the development of the boiler, work was carried out to create a modern low-emission combined burner device for it. For this purpose, comprehensive computational and theoretical studies were carried out at the National Research University “MPEI”. In the result the main regularities of the processes of ignition and combustion of gaseous and liquid fuels, heat and mass transfer processes and the pollutants formation in confined conditions of fire tubes were identified [11, 12].

The development of the range of burner devices was carried out simultaneously with the design of the corresponding range of boilers with a capacity of 0.5 to 3.0 MW and was also based on computer modelling of burning processes and gas dynamics. The need to domestic burners developing was due to the fact that the fire-tube boilers currently presented on the Russian market are equipped with burners from foreign manufacturers, which are not normally designed for crude oil combustion. Thus, in addition
to the task of creating a new burner that provides the necessary reliability, efficiency and environmental safety, the issue of import substitution was also solved.

In accordance with the task, the burner device must ensure not only stable ignition and complete combustion of crude oil in the confined volume of the fire tube with minimal chemical underburning in the operating range of the boiler loads from 40 to 100% of the rated load, but and reduced nitrogen oxides emission.

Combustion processes modelling of using CFD-methods have shown that the working processes occurring in the specific confined conditions of the fire tube are significantly different from similar processes occurring during the fuel combustion in open furnace devices of water-tube boilers. First of all, this applies to the conditions of fuels ignition and convective heat exchange on the walls of the fire tube. For this reason, the straitened of the fire tube space and a significant proportion of convective heat transfer were taken into account in the mathematical model of working processes. To ensure the necessary accuracy of the simulation, a computational grid containing about 20 million data points was developed (Figure 5). A cluster with 120 cores and 640 gigabytes of RAM was used for the calculations. The calculated studies made it possible to identify the main physical patterns of working processes and determine their impact on the technical, economic and environmental characteristics of the equipment.

![Figure 5. View of the three-dimensional geometric model and the computational grid for modelling from the burner device side (a) and its general view (b).](image)

The proposed design of the burner device was based on the principle of stage fuel combustion developed at the National Research University "MPEI" [13]. The stage combustion concept applied to
the developed burner device under was to organize additional air flows to various fuel combustion zones to improve the conditions of its burnout and reduce the emission of nitrogen oxides. To optimize the design, computer models of various versions of the burner device were developed and numerical experiments were performed to study the processes of sputtering, ignition, burning of crude oil and reserve fuels (natural gas and diesel fuel) and the emission of nitrogen oxides and carbon monoxide, depending on the design and operating parameters [14, 15].

Numerical experiments included studies of the influence of the angle of the axial blades installation in the peripheral air flow and the modes of stage combustion, implemented due to various design options of the burner elements. The conducted numerical experiments allowed us to propose an optimal design of a combined burner device with a perforation in the central disk-diffuser, which ensures reliable operation on all the studied fuels with low nitrogen oxide emissions (Figure 6).

![Figure 6. Design of a low-emission burner for a fire-tube boiler: 1 – gas collector; 2 – axial blades; 3 - adjustment ring; 4 - outlet neck; 5 - perforated disc; 6 - pylon-fairing; 7 - gas nozzles.](image)

The design of the burner device provides a sequential air supply to the liquid fuel spray cone in the following ratios (Figure 7): through the central hole in the disk (20.4% of the total amount of air), through radial slots and holes in the disk sectors (15.9%) and, finally, by a swirling flow along the periphery (63.7%).

Thus, a gradual increase in the values of local excess air in the ignition and active combustion zones is realized. As a result, favourable conditions are provided for fuel burnout and reduced nitrogen oxide emissions taking into account polydispersity of the crude oil droplets and, accordingly, the different rates of their heating and the exit of the vapor phase from the liquid droplets.

Numerical experiments have shown that there are stable symmetrical zones of reverse flow in the central region responsible for the ignition of crude oil at all loads (Figure 8). At the rated load the crude oil ignition occurs both along the inner and outer boundaries of the spray cone. As the load decreases, the ignition at the outer boundary of the spray cone stops and shifts only to the inner boundary (Figure 9). This is due to the fact that larger oil droplets do not have time to warm up and evaporate at the outer boundary, where the temperatures of the recirculating gases are lower than in the zones of reverse currents in the centre of the fire tube.
Figure 7. Flow diagram in a vortex burner: 1 - pre-chamber flow; 2 - peripheral zone of reverse flows; 3 - central ignition zone; 4 - flame front; 5 - back critical point; 6 - reverse flow zones in the diffuser; 7 - peripheral ignition zone.

Figure 8. Axial velocity field, m/s, in the zone of reverse currents (a) and temperature field, °C, in the fire tube (b) for crude oil burning at rated load.
Figure 9. Temperature fields, °C, in a fire tube for crude oil burning at a load of 60 % (a) and 40 % (b) of the rated load.

Numerical experiments have confirmed that the proposed burner device provides stable ignition and complete combustion of crude oil in the entire range of operating loads from 40 % to 100 % of the rated load. Moreover, has reduced the maximum gas temperatures in the active combustion zone (which increases the reliability of the metal of the fire tube) and reduced the emission of nitrogen oxides over the entire operating load range due to the implementation of stage combustion. Thus, the emissions of nitrogen oxides at the rated load are 10-15% lower than those of modern foreign analogues. At the same time, the gas temperatures at the outlet of the turning chamber remained at a sufficient level, providing good conditions for complete fuel burnout.

The emission of nitrogen oxides (160-190 mg/m$^3$) and carbon monoxide (less than 50 mg/m$^3$) in the entire range of working loads during the combustion of crude oil was lower than the values, established GOST 30735-2001 "Hot water heating boilers with a heating capacity of 0,1 to 4,0 MW. General technical conditions" for hot water boilers with a capacity of up to 4 MW of class II when burning heavy liquid fuels (300 mg/m$^3$ for nitrogen oxides and 160 mg/m$^3$ for carbon monoxide in dry gases in terms of the excess air coefficient equal to one).

As a result of the completed research, an autonomous energy – efficient complex was developed and created—a block-modular boiler house, including two hot-water boilers with a capacity of 3.0 MW each (Figure 10). In the course of the conducted thermal engineering tests of the BMBH, the compliance of their actual operating parameters with the design indicators in the entire load range was confirmed. The actual boilers efficiency was guaranteed to exceed 94 % at all loads during the test period (Figure 11).
Figure 10. Installation of the boiler in the block-modular boiler house (BMBH) before sending it to the customer.

The results of the tests confirmed that boilers operate with an efficiency above 94 % over the entire load range from 36 to 105 % of the rated load. With a decrease in the load of boilers, their efficiency increases and at minimum loads exceeds 96 %. The minimum efficiency of boilers during the acceptance tests was 94.5 - 95.2% and the average efficiency was 95.2 - 95.7%.

Figure 11. Dependence of the exhaust gas temperature, O₂ concentration in the exhaust gases and efficiency on the load of boiler No. 1 (a) and boiler No. 2 (b).
4. Conclusion
The developed computer models of burner devices and conducted numerical experiments using CFD methods to study the processes of ignition, fuel burnout and emission of nitrogen oxides and carbon monoxide, depending on the design and operating parameters, made it possible to identify and study in detail the main regularities of physical and chemical and heat-and-mass transfer processes during the combustion of crude oil in the poorly studied specific confined furnace conditions of low-power fire-tube boilers.

Based on the results of the research, a new fire-tube boiler with a remoted economizer for placement inside the BMBH and a new combined low-emission burner device were developed, created and tested, which have a number of advantages compared to foreign analogues.

The operational and environmental characteristics of the developed boilers and burner devices are confirmed by certification tests for compliance with the Technical Regulations of the Customs Union.

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