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THE EFFICIENCY OF LOW-POWER SOLID-FUEL WATER BOILERS

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ЭФФЕКТИВНОСТЬ МАЛОМОЩНЫХ ТВЕРДОТОПЛИВНЫХ ВОДОГРЕЙНЫХ КОТЛОВ

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Abstract. Burning fuel in large quantities when using hot water boilers leads to losses, which reduces the energy conversion efficiency of the boiler. Therefore, there were mainly small energy-saving stoves designed to burn fuel. The author proposed to use a small boiler with a firebox with a vertical grate. A small boiler with an adjustable grate water heater with a capacity of 50 kW was installed in the boarding school building. Combustion of any fuel in such a furnace had following results: a) the productivity of the boiler unit had been increased to 79–81 %; b) heat loss reduced by 2 times and harmful emissions into the atmosphere in 1.5 once. The costs of providing thermal energy compared to other operating boiler houses amounted to 14 400 somoni (1 200 dollars). This is 18 % less than the costs of the previous heating season without using the proposed boiler. The efficiency of heating processes in the boiler was assessed during one heating season.

Key words: hot water boiler, furnace, vertical grate, thermodynamic analysis, energy efficiency, heat loss with flue gases, fuel combustion temperature

Аннотация. Сжигание топлива в больших количествах при использовании водогрейных котлов приводит к определенным потерям, что снижает КПД котла. Поэтому для сжигания топлива были разработаны малогабаритные энергосберегающие печи. Автор предложил использовать малогабаритный котел с топкой с вертикальной колосниковой решеткой. Малогабаритный котел с водонагревателем с регулируемой колосниковой решеткой мощностью 50 кВт был установлен в здании школы-интерната. Сжигание любого топлива в такой топке привело к следующим результатам: а) производительность котлоагрегата увеличилась до 79–81 %; б) потери тепла сократились в2 раза, а вредные выбросы в атмосферу – в 1.5 раза. Затраты на обеспечение тепловой энергией по сравнению с другими действующими котельными составили 14 400 сомони (1 200 долл.). Это на 18 % меньше затрат предыдущего отопительного сезона без использования предлагаемого котла. Эффективность тепловых процессов в котле оценивалась в течение одного отопительного сезона.

Ключевые слова: водогрейный котел, топка, вертикальная колосниковая решетка, термодинамический анализ, энергоэффективность, потери тепла с дымовыми газами, температура сгорания топлива

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Introduction

In Tajikistan, one of the main types of accessible and economically viable fuel is coal and lignite. At the same time, coal has disadvantages, such as high heat loss due to mechanical and chemical underburning, and a negative impact on the environment due to dangerous emissions of carbon dioxide and combustion products. In this regard, low-power solid fuel hot water boilers are traditionally used for heating and hot water supply [1].

The main types of fuel for such stoves are wood, coal and manure – local fuel, which is waste from livestock farming. Solid fuel obtained from different deposits differ from each other in their properties and combustion products.

The main values of the thermophysical properties of coal from some deposits in Tajikistan are presented in Table 1.

The efficiency of thermal processes in the boiler was evaluated using the first and second laws of thermodynamics. Based on the energy balance, the boiler efficiency was assessed [2–4]. The work is based on well-known research in the field of heat generating plants by K. F. Roddatis, A. N. Poltaretsky, V. M. Fokin, E. G. Volkovyskiy, N. B. Lieberman, Yu. L. Gusev. It is also necessary to note the works of A. V. Vikhrov and L. K. Ramzin, which address the issues of the organization of solid fuel combustion and the design features of boilers with furnaces of layered construction.

Since the 90s of the twentieth century, research has been carried out on the conditions for the efficient combustion of fuels of various compositions without the formation of harmful emissions into the atmosphere. Research is mainly aimed at identifying methods, mechanisms for controlling and organizing fuel combustion processes with minimal emissions of harmful substances into the atmosphere. The most effective methods for calculating thermal conditions in a limited volume are described in the works [5–8]. Research on this topic was conducted by [9–11].

Table 1
Таблица 1

Thermophysical properties of coal of the main deposits in Tajikistan
Термофизические свойства угля основных месторождений Таджикистана

Name of the deposits	Heat of combustion, kJ/kg	Humidity, %	Ash content, %	Yield of volatile substances, %
Hakimi	27 017–32 573	5.2–17.4	4.8–19.7	26.8–46.9
Fan-Yagnob	32 260	0.35–1.88	3.9–24.5	23.1–36.9
Sayat	30 919	4.9	32.3	32.43
Ziddi	28 085–32 175	3.4–10.2	12.6–33.7	4.9–25.8
Mienadu	35 026	1.1	11.1–30	4.9–25.8
Ravnou	31 694	0.3–9.6	6.3–34.8	29.3–38.3
Nazar-Aylock	35 145	0.78–4.66	1.2–4.2	3.0–5.0
Shurab	27 964	13.1	12.5	34.8

However, in existing publications, practically no attention is paid to optimizing the operating modes of low-power solid fuel water boilers when operating on coal with high ash content. In existing small boilers there is no solid fuel discharge, the firebox has only one burner, and the fireplace grate is fixed. My colleagues and I have also devoted our research to exploring this topic [12–14]. In the design of a small boiler proposed by the author, all types of fuel are burned; the grate inside the firebox is movable in the vertical direction. A distinctive feature of the circuit is the presence of a small water heater boiler. The volume of the firebox has increased for burning other solid fuels, taking into account their characteristics.

The purpose of the study is to develop the design of a hot water boiler for efficient combustion of fuels of various compositions. To develop the design of a water-heating boiler, a mathematical description of the combustion processes of fuel when the volume of the combustion space changes was carried out. A design of a water-heating boiler with a movable grate was developed, and experimental studies of the combustion of high-ash fuel on a movable grate were carried out.

The thickness of the radiating layer is calculated according to the formula:

$$S = 3.6 \cdot V_t / F_{st},$$

where V_t is the volume of the furnace chamber, m^3, F_{st} – the surface area of the furnace walls, m^2.

The issues related to the energy and heat release analysis of the efficient combustion of solid fuel can be quite broad and complex. However, here are several factors that should be considered when analyzing the efficiency of low-power solid fuel hot water boilers:

1. A method used to conduct an energy analysis of the solid fuel combustion.
2. Factors affecting the efficiency of solid fuel combustion.
3. Parameters and indicators used to analyze heat release in solid fuel combustion.
4. Existing technologies for improving the efficiency of solid fuel combustion.
5. Environmental aspects that should be considered in the analysis of solid fuel combustion.
6. Opportunities to optimize the solid fuel combustion process to achieve maximum energy efficiency and minimum exhaust emissions.

Exergetic analysis is one of the tools for evaluating the effectiveness of thermodynamic processes. It allows us to determine the maximum possible use of energy that can be extracted from the system to perform useful work.

When exergetic analysis is applied to boilers, it helps to determine the level of energy losses associated with processes such as heat exchange, diffusion, friction and others. This makes it possible to identify problem areas that can be optimized to increase boiler efficiency.

Object and methods of research

The object of the study is a hot water boiler unit with the vertical grate of furnace.

The thermodynamic efficiency of a system at equilibrium includes:

1. Efficiency (reduces the energy conversion efficiency) is the ratio of useful energy used to energy expended. In the case of a reversible transition, efficiency can be defined as the ratio of work obtained to heat expended.
2. Thermal efficiency is the ratio of heat generated to heat consumed. In a reversible process, the thermal efficiency will be maximum and equal to unity.
3. Exergy efficiency is the ratio of released exergy (useful work) to stored exergy (expended heat). In a reversible process, the exergy efficiency will be equal to unity.

In an adiabatic process, the efficiency will be high since the system does not lose or release thermal energy.

Let us consider a method for studying technological and exergy processes based on the second law of thermodynamics. The action of these processes occurs under conditions of interaction of the system with an equilibrium environment. Environmental parameters ensure the constancy

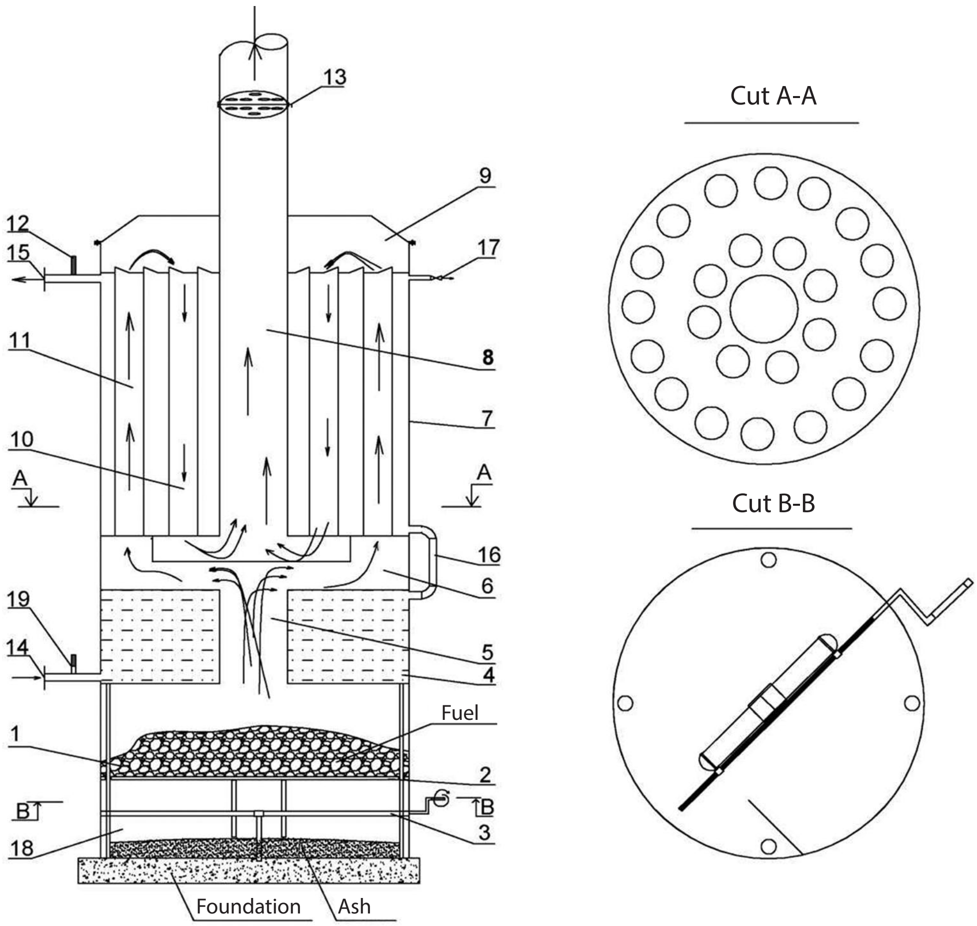

Fig. 1. Diagram of a hot-water sectional solid fuel boiler: 1 – firebox; 2 – movable grate; 3 – lifting mechanism; 4 – the beam-receiving surface (additional drum); 5 – the transition gas pipe; 6 – the lower gas distribution chamber outlet; 7 – the main drum of the boiler; 8 – the central exhaust pipe; 9 – upper gas distribution chamber; 10 – exhaust pipes with descending flows; 11 – exhaust pipes with ascending flows; 12 – thermometer; 13 – chimney with gate; 14 – cold water inlet pipe; 15 – heated water outlet pipe; 16 – transition pipe; 17 – air outlet pipe; 18 – ash pan; 19 – thermometer
Рис. 1. Схема водогрейного секционного твердотопливного котла: 1 – топка; 2 – подвижная колосниковая решетка; 3 – подъемный механизм; 4 – лучевоспринимающая поверхность (дополнительный барабан); 5 – переходная газовая труба; 6 – нижняя газораспределительная камера отводная; 7 – основной барабан котла; 8 – центральная газоотводная труба; 9 – верхняя газораспределительная камера; 10 – газоотводные трубы с нисходящими потоками; 11 – газоотводные трубы с восходящими потоками; 12 – термометр; 13 – дымоход с шибером; 14 – патрубок входа холодной воды; 15 – патрубок выхода нагретой воды; 16 – переходной патрубок; 17 – патрубок выпуска воздуха; 18 – зольник; 19 – термометр

of the thermodynamic system, and energy is converted into work. There are several types of work. To improve the efficiency of the boiler, the concept of chemical filling can be used [2–5, 10–14].

If calculate the exergy balance, you can take into account the excess lost in the process of switching between components:

$$E_{ent} = E_{ex} + \Sigma E_{D_i} ,$$

where E_{ent} is exergy supplied to the object with flows of matter and energy;
E_{ex} – exergy leaving the installation;
E_{Di} – exergy losses.

The article discusses the equipment of a furnace with a variable volume of combustion space. Coal from the Ziddi deposit was used to produce flue gases. Their temperature was 300 K. In the mixing chamber, the combustion products were diluted with air ($T_o = 293$ K, moisture content $d = 0.01$ kg/kg, $p = 9.8 \cdot 10^4$ Pa. The air consumption for complete combustion of 1 kg of fuel is *46.7 m³/kg* [4].

The exergy balance for the furnace is determined by the formula:

$$E_t = E_{cp} + \Delta E_{the\ env.} + \Delta E,$$

where E_t is exergy of the initial fuel $E_t = 5\,383$ kcal/kg $= 22\,538$ kJ/kg;

E_{cp} – exergy of combustion products in the furnace at adiabatic combustion temperature;

$\Delta E_{the\ env.}$ – exergy of the heat flow into the environment;

ΔE – тotal losses in the furnace.

According to calculations, the energy conversion efficiency of the furnace can be about 89 %. The operation of the furnace with a variable volume of combustion space is 15-20 % more efficient than standard furnace.

Results

Therefore, the exergy efficiency of the boiler η_{ex} characterizes the share of usefully used exergy:

$$\eta_{ex} = \frac{E_{cost}}{E_{ser}} = \frac{E_{exit} - E_{redu}}{E_{entrance} - E_{redu}},$$

where E_{cost}, E_{ser} are spent and used exergy, respectively; E_{redu} – common transit exergy, that is, exergy that passes from the entrance to the equipment to its exit without participation in energy exchange processes. For the waste heat boiler in this case, the transit exergy includes the exergy of the feed water flows $E'_{v,a}$ and the air E'_{air} as well as the physical exergy of the exhaust gas flow of the soot production. The coal from the Ziddi deposit has the following characteristics of its combustion, m³/kg: $V_0^0 = 5.51$; $V_{CO_2} = 0.915$; $V_{N_2} = 4.2$; $V_{H_2O} = 0.615$; $V_{cp} = 5.73$. For coal from the Ziddi deposit ($Q_p^n = 22500$ kJ/kg) the exergy of coal combustion products was calculated (table 2, 3).

Let us determine the exergy of flue gases in the mixture obtained by diluting the combustion products of coal with air in the amount of *46.7 m³/kg;* $p = p_0 = 9.8 \cdot 10^4$ Pa, $T_0 = 293$ K, $W_0 = 0.01$ kg/kg up to the temperature of the mixture $t_{sm} = 573$ K.

There were firebox characteristics using in the study:

- hearth surface was 0.2826 m²;
- side surface – 0.7536 m²;
- ceiling surface – 0.2703 m²;
- the inner surface of the central exhaust pipe – 0.314 m²;

Table 2
Таблица 2

Exergy of the coal from the Ziddi deposit
Эксергия угля Зиддинского месторождения

V_{cp}^0, m³/kg	Mole fractions			Moisture content X_{z0}, kg/kg	Chemical effect of the combustion process $e0_{cp}$, кJ/kg
	N_2	CO_2	H_2O		
6.603	0.789	0.1750	0.0983	0.0162	1046

Table 3
Таблица 3

Thermodynamic parameters of flue gas components
Термодинамические параметры компонентов дымовых газов

Substances	V_f, m³/kg t	N_f, kmol/m³	h, kJ/kmol	h_0, kJ/kmol	Δh, kJ/kmol	$N_i\Delta h$, kmol/kg t	S, kJ/(kmol·K)
CO_2	0.916	0.0412	12 519	761	11 751	478	30.43
N_2	57.20	2.551	8 789	581	8211	20 949	21.64
O_2	15.18	0.677	9 100	590	8510	5 769	22.26
H_2O	1.75	0.071	10 351	673	9672	818	25.56
Total	78.64	3.511				28 020	

- the surface of the ceiling of the flue pipe – 1.2265 m^2;
- furnace volume – $1.228525 \cdot 10^{-1}\ m^3$.

The mass flow rate of combustion products during the combustion of 1 kg of solid fuel is determined by the dependence:

$$G_0 = 1 - \frac{A^p}{100} + 1.306 \cdot \mu V^0,$$

for V [kg] fuel:

$$G = B \cdot G_0 = B\left[1 - \frac{A^p}{100} + 1.306 \cdot \propto V^0\right] = f\left(B, \propto, V^0\right)$$

$$\text{or} \quad t(x) = t_0 + exp\left[-\frac{k\pi d_{g.tr.h}}{cf\left(B, \mu, V^0\right)} x\right].$$

In the process of energy and exergy analysis of the efficiency of operation of low-power solid fuel hot water boilers by installing a movable grate, it was found that the variable volume of the furnace space, helps us to reduce fuel consumption, and also contributes to the afterburning of volatile gases and unburned pulverized fractions of coal.

The calculation showed that the efficiency of the furnace was 89 % and fuel consumption decreased by 15–20 %. Heat loss from external gases amounted to 8.8 %; heat losses from the use of mechanical fuel amounted to 17.4 %. The productivity of the boiler unit has been increased to 79–81 %. On the issue of emission of harmful substances into the atmosphere, a boiler model with removable grates and combustion technology is considered in the Set of rules 89.13330.2012[1] .

Conclusion

Based on the research carried out, an urgent scientific problem has been solved – a low-power solid fuel boiler with a movable furnace and the possibility of regulating volumetric thermal voltage has been developed for use in the water heating system of detached buildings to ensure the efficiency of solid fuel combustion. The proposed boiler design ensured a minimum airflow rate for complete combustion of solid fuel in the boiler furnace and a maximum direct heat transfer coefficient in the combustion chamber. The study showed a number of findings:

1. The maximum efficiency of the proposed furnace when burning various solid fuel (coal) is established by changing the furnace space of the boiler using a movable grate, which allows us to adjust the volume of the furnace space.
2. Reducing and increasing the furnace space of a small water heater helps maintain the required boiler temperature, which leads to a reduction in the content of nitrogen oxides by 20–25 %.
3. In the course of economic research and implementation of the developed project, a small boiler with an adjustable grate water heater with a capacity of 50 kW was installed in the boarding school building. Over the period of operation, one season, compared to other existing boiler houses, cost 14 400 somoni (1.200 US dollars), which is 18 % less than the initial costs of previous years for the provision of thermal energy.

Based on the results of the study, a comprehensive automated control system for boiler operating modes will be created, providing regulation of the volume of the combustion space, air supply and removal of combustion products.

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