

Determination of the thermotechnical measures of the condensing water heating boiler's high-temperature section

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Abstract. This paper presents the experimental data processing results, obtained during tests of the fuel-saving condensing water heating boiler, that has been designed by the employees of the Belgorod State Technological University named after V.G. Shukhov. The mentioned boiler can be used in heat supply for residential, industrial and office buildings. The paper presents the justification of the stand-alone systems actuality use for heat supply of consumers with different needs, and also the use of such systems as a heat-generating unit in condensing boiler type as a heat source. It demonstrates the functional diagram and description of the test bench for the condensing water heating boiler specimen with heat production of 250kW, and also gives an operation description of this test bench. The paper presents the heat transfer agent values of flow rates and temperatures, obtained during the boiler's tests under different loads. It also describes the test result processing methods, presents formulas for calculations. It presents dependences of the energy carrier parameters, and also heat transfer coefficients in the boiler's high-temperature section elements on its load. The results analysis of the experimental data processing has been conducted. The conclusions about prospective use of the suggested condensing water heating boiler as the heat-generating unit in heat supply stand-alone systems for consumers with different needs have been formulated.

1. Introduction

Rational control of use and conservation of different energy resources, that residents of cities and other communities consume, is the most vital factor, which is aimed at achieving stable and effective fuel and energy resources consumption [1-2]. One of the most energy-intensive system in the city is a heat supply system for consumers with different needs.

At present, in most European countries for the heat supply of the consumers with different needs (residential, social and industrial buildings and facilities) a stand-alone systems of heat supply are being used [3-4]. In recent decades in the Russian Federation use of such systems has increased [5]. Among advantages of the heat supply stand-alone systems can be pointed out the following factors [6-8]:

- no need for long-distance heat supply system network, and as a result losses elimination of heat energy and heat transfer agent inside the network;
- simpler control of heat delivery by the heat source, and as a result heat loss decrease in the heat supply system;
- less expensive maintenance and equipment repair in comparison with the central heating systems.

A tendency of increased use of condensing water heating boilers in the new stand-alone heat supply systems as heat source is being observed in recent years. In this type of boiler products of combustion



get cooled down to the temperature when water vapor condensates, which is a part of the organic fuel combustion products. Some countries are trying to replace boilers in stand-alone heat supply systems completely by the boilers and water heaters of condensing type [9-11]. This type of boilers conserves up to 15% of fuel.

The employees of the Belgorod State Technological University have developed the design of the condensing water heating boiler for its use in the stand-alone heat supply systems for consumers [12]. This boiler is a double-circuit boiler. In the first circuit – high-temperature section – fuel burns and it results in a heat transfer agent production, which is then being delivered for the consumer's heating needs. In the second circuit – contact-recuperative section – the gaseous fuel combustion products experience deep cooling and most of the water vapors, that are part of it, condense, also heat transfer agent is being prepared for consumer's hot water supply. The high-temperature and contact-recuperative sections are connected by the adiabatic section, where isoenthalpic cooling takes place and combustion products get moisturized at the contact with pulverized into the gas flow water. The functional diagram of the condensing water heating boiler is presented in Figure 1.

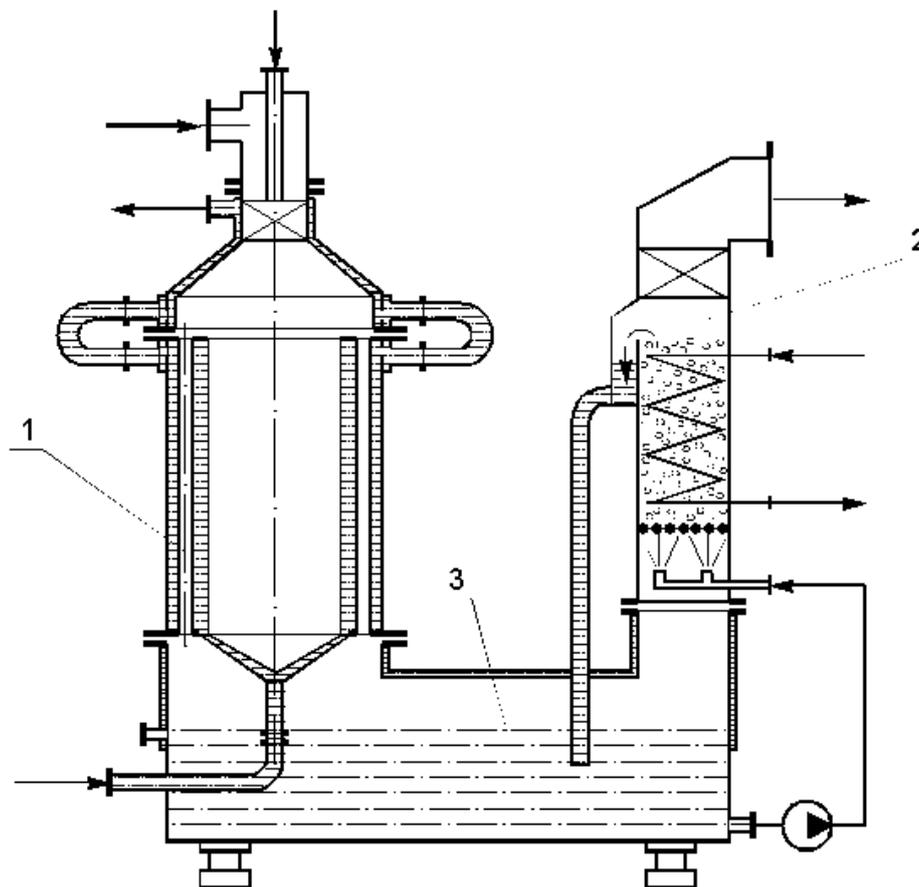


Figure 1. Functional diagram of the condensing water heating boiler: 1 – high-temperature section; 2 – contact-recuperative section; 3 – adiabatic section.

To determine thermotechnical and hydraulic characteristics of the condensing water heating boiler tests were conducted, using a mentioned-above boiler with heat production of 250kW. The objective of this paper is the presentation of the results of the considered condensing water heating boiler's high-temperature section experimental research.

2. Materials and Methods

To conduct experimental research of the condensing water heating boiler operation and determine thermotechnical measures during its operation a test bench was constructed [13], a description of which can be seen in Figure 2.

Two shell-and-tube heat exchangers, besides the boiler, were introduced into the thermal equipment of the test bench. One of them imitates a consumer of the heating system. Into the shell side of this heat exchanger enters the water, which was heated up in the boiler's high-temperature section. It gets cooled here by the flowing inside tubes cold tap water to the temperature of the return water in the heating system. Water that was cooled in the shell side of the heat exchanger returns to the boiler.

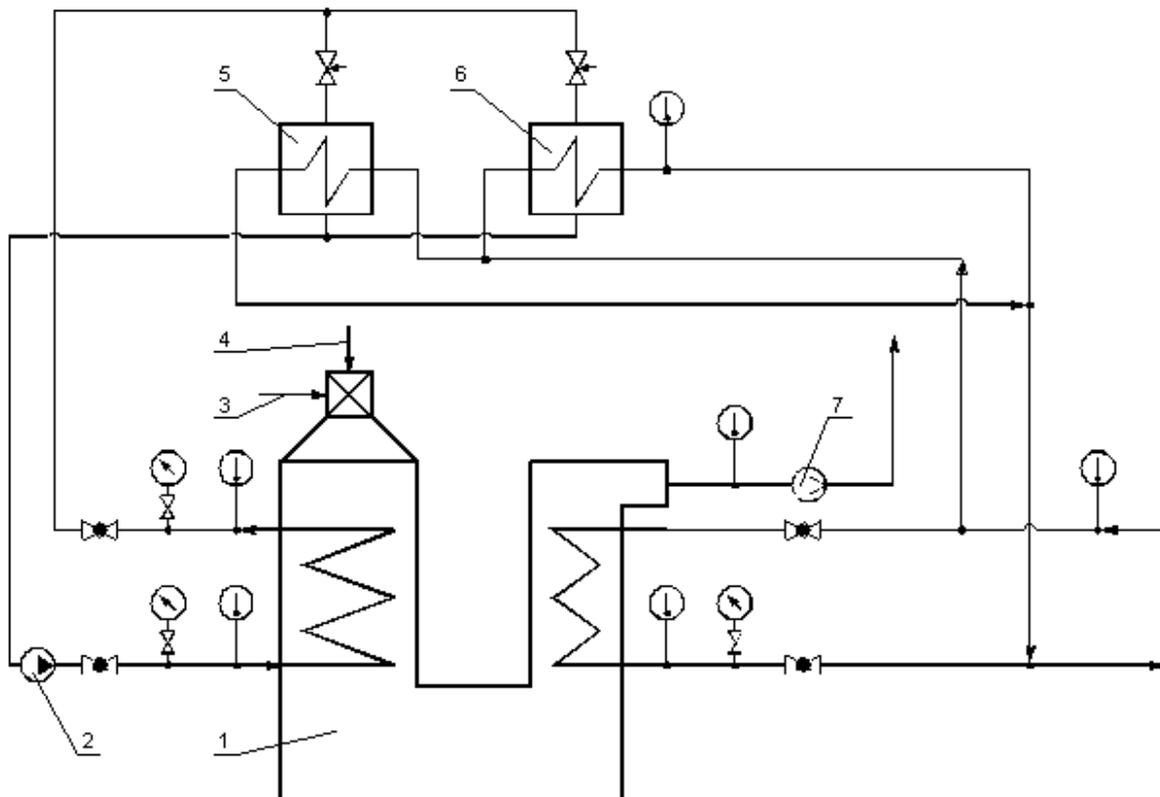


Figure 2. Test bench diagram of the condensing water heating boiler: 1 – condensing water heating boiler; 2 – pump of the heating system; 3 – air; 4 – natural gas; 5 – heat exchanger, which imitates a consumer of the heating system; 6 – water heater for the hot water supply needs; 7 – flue gas fan.

The purpose of the second heat exchanger is water heating for drinking and household needs, which flows in the shell side, to the temperature of water for hot water supply needs. Water is heated with the aid of cooling by water flowing in the shell side, which was prepared in the boiler's high-temperature section. Afterward, heated in the mentioned heat exchanger water mixes with water that was heated in the contact-recuperative section of the condensing water heating boiler.

Therefore, the second heat exchanger controls the relation of the heat, which is directed by the system to cover the heating load and hot water supply load. This kind of control became an important part in systems with comparable values of heating and hot water supply loads, because at nominal boiler's load heat production of the boiler's high-temperature section is near 75%, and heat production of the contact-recuperative section is near 25% from the boiler's total capacity.

The test bench works in the following order. The high-temperature section of condensing water heating boiler, which basically is a fire-tube and gas-tube water heater, and also shell side of the heat

exchangers get filled with salt-free water, and into the tubes of the contact-recuperative section's tube bundle gets cold water of drinking and household quality, which flows in it with constant flow rate. To cool down water in heat exchangers, which was heated in the boiler's high-temperature section, into its tube side cold tap water is being directed. During the test process water heated in the heat exchanger, which imitates consumers of the heating system, was dumped into a sewage system. The cooling water after exiting the heat exchanger, which is used to control the relation of the heating system and hot water supply loads, gets mixed with water, which was heated in the contact-recuperative section, and then dumped into the sewage also.

During the thermotechnical characteristics determination of the condensing water heating boiler, the following parameter measurements were conducted: natural gas flow rate, excess air ratio, water temperature at the inlet and outlet of the boiler's contact-recuperative section, and also combustion products temperature at the exit from the high-temperature section and the boiler. Ranges of the measured during tests values are presented in Table 1. This Table also contains, for comparison reason, calculated values of the mentioned-above parameters, which were given or determined during experimental boiler specimen design [14].

Table 1. Main calculated and actual parameters of the condensing water heating boiler.

Parameter name	Parameter value	
	calculated	actual
Natural gas flow rate, m ³ /hr.	23.5	11.0...23.28
Excess air ratio	1.10	1.09...1.14
Water temperature, °C:		
at the inlet of high-temperature section	60	50...62
at the outlet of high-temperature section	95	70...92
at the inlet of contact-recuperative section	≈ 10	≈ 10
at the outlet of contact-recuperative section	55	40...64
Combustion product temperature, °C:		
at the outlet of high-temperature section	250...370	177...336
at the exit from the boiler	35	20...42

The results, obtained during tests, are very close to the calculated values. It has to be noted, that temperature values of heat transfer agents, preparation of which was conducted in the boiler's high-temperature and contact-recuperative sections, meet requirements of the Russian Federation normative documents, that regulate corresponding heat transfer agent parameters.

The boiler's high-temperature section thermotechnical characteristics determination, using obtained during the experiment values, required calculations of fuel combustion, parameters of gas in the furnace, at the exit from the high-temperature section and at the exit from boiler, boiler's heat balance preparation, calculation of the heat transfer in a furnace chamber (fire-tube), calculation of the heat transfer in flue-tubes.

During the process of calculation of the fuel combustion using standard methods were determined volumes of dry and wet combustion products and components included in it, that can be found in 1 m³ of burnt natural gas. This temperature was calculated by the following formula, °C

$$t_a = \frac{Q_i^d + i_f + I_a}{V_g^n c_{p.c}} \quad (1)$$

where Q_i^d – lower heating value of natural gas combustion on a dry basis; i_f – heat content of fuel; I_a – heat content of air delivered for combustion; V_g^n – volume of combustion products per unit volume of burnt gas in normal conditions; $c_{p.c}$ – mean volumetric heat capacity of combustion products.

The heat capacity of the combustion products depends on its temperature values. Therefore, the calculation of the adiabatic combustion temperature is done by the method of successive approximations. The calculation results can be found in Table 2.

Table 2. Dependence of the adiabatic combustion temperature on the excess air ratio.

	Parameter name					
Excess air ratio	1.09	1.10	1.11	1.12	1.13	1.14
Adiabatic combustion temperature, °C	1907	1895	1882	1869	1857	1845

Further calculations required determination of the combustion product parameters in normal conditions and operating conditions at boiler's measuring points: in the furnace at an adiabatic temperature (parameters are given the index G1), at the exit from boiler's high-temperature section (G3) and at the exit from the boiler (G5). The density of the combustion products in normal conditions with known volumes of dry and wet gases and components, included in it, was determined as the density of the gases mixture using the additivity principle. The combustion products density in the boiler's measuring points in operation conditions, assuming that gas pressure is changing marginally and close to the atmospheric, were calculated by the formula, kg/m³

$$\rho_G = \rho_G^\circ \frac{273}{273 + t_G} \quad (2)$$

where ρ_G° – combustion products density in the boiler's measuring point in normal conditions; t_G – combustion products temperature in the boiler's measuring point.

The volumetric flow rates in normal and operation conditions, and also the mass flow rate of combustion products in the boiler's measuring points were determined. Having in mind that in the process of combustion products cooling in the adiabatic and contact-recuperative sections of the boiler their moisture content is changing, so the mass flow rate of gases at the exit from the boiler can be determined by the formula, kg/s

$$G_{G5} = G_{d.g} (1 + x_{G5}) \quad (3)$$

where $G_{d.g}$ – mass flow rate of dry gases; x_{G5} – gases moisture content at the exit from the boiler.

Enthalpy of the combustion products in the boiler's measuring points were determined by the formula, kJ/kg of dry gases

$$I_G = (c_{d.g} + c_{w.v} x_G) t_G + r_0 x_G \quad (4)$$

where $c_{d.g}$ – mean specific isobaric heat capacity of dry gases; $c_{w.v}$ – mean specific isobaric heat capacity of water vapor; x_G – combustion products moisture content; r_0 – heat of water vapor condensation in normal conditions.

Heat flux with combustion products in the boiler's measuring points were determined by the formula, kW

$$Q_G = I_G G_{d.g} \quad (5)$$

As a result of the boiler's heat balance preparation were determined efficiency and flow rates of the heat transfer agent, which is directed for the consumer's heating needs. The efficiency of the condens- ing water heating boiler was determined using indirect heat balance equation

$$\eta = 1 - (q_2 + q_3 + q_4 + q_5) \quad (6)$$

where q_2 – portion of heat loss due to the exiting from the boiler gases; q_3 – portion of heat loss due to incomplete combustion; q_4 – portion of heat loss due to unburned carbon; q_5 – portion of heat loss due to external cooling.

The portions of heat loss q_3, q_4, q_5 were taken in accordance with the normative method of the boiler's thermal design recommendations. The portion of heat loss due to the exiting from the boiler gases was calculated as a relation of the heat flux with combustion products at the exit from the boiler to the heat flux with combustion products in the furnace at the adiabatic combustion temperature

$$q_2 = Q_{G5}/Q_{G1} \quad (7)$$

The heat transfer agent flow rate, which is directed for the consumers heating needs, was calculated by the formula, kg/s

$$G_{h.s} = \frac{Q_{h.s}}{i'_{dnw} - i'_{mww}} \quad (8)$$

where $Q_{h.s}$ – amount of heat, which is usefully utilized in the boiler's high-temperature section; i'_{dnw} – enthalpy of water at the entrance and exit of the boiler's high-temperature section.

Amount of heat, usefully utilized, which was transferred from the combustion products to the being heated water in the boiler's high-temperature section was determined as a difference between the heat fluxes with combustion products in the furnace at an adiabatic combustion temperature and at the exit from the boiler's high-temperature section with consideration of the heat losses into the atmosphere through the boiler's walls, kW

$$Q_{h.s} = (Q_{G1} - Q_{G3}) \cdot (1 - q_5) \quad (9)$$

The radiation heat transfer in the furnace calculation using standard method, which can be found in the normative method of boiler's thermal design, resulted in determination of the temperature and heat content of combustion products at the exit from the boiler's furnace upon condition of radiation heat transfer only, and also amount of heat, transferred in the furnace chamber by radiation, was calculated.

The combustion chamber in the considered boiler is a reverse-flow type and made as a fire-tube, where combustion products speed is very high and the portion of heat, which is being transferred in the furnace by convection from the fire-tube's inner surface, is considerable. Therefore, it was worthwhile conducting the amount of heat determination, which is being transferred in the fire-tube from gas to the being heated heat transfer agent by convection and also calculate temperature and heat content of the gasses, that are exiting the combustion chamber considering convective heat exchange in it.

The heat exchange in the combustion chamber calculation resulted in the determination of the total amount of heat, which combustion products release in the fire-tube by radiation and convection, and also total heat transfer coefficient in the furnace, which was determined by the basic equation of heat transfer, $W/(m^2 \cdot K)$

$$K_f = Q_f / (F_f \cdot \Delta t_f) \quad (10)$$

where Q_f – amount of heat released by the gasses in the fire-tube by radiation and convection; F_f – fire-tube's inner surface area; Δt_f – mean temperature difference in the fire-tube.

To determine the heat transfer coefficient in the flue tubes amount of heat was calculated, which is being transferred by gases moving in the flue tubes; water flowing in the shell side of the boiler's high-temperature section. This amount of heat was determined as a difference between the amount of heat usefully utilized in the high-temperature section and the amount of heat released by gases in the fire-tube.

$$Q_{s.t} = Q_{h.s} - Q_f \quad (11)$$

The heat transfer coefficient in the flue-tubes was determined by the basic equation of heat transfer, $W/(m^2 \cdot K)$

$$K_{s,t} = Q_{s,t} / (F_{s,t} \cdot \Delta t_{s,t}) \quad (12)$$

where $F_{s,t}$ – surface area of heat transfer in flue tubes; $\Delta t_{s,t}$ – mean logarithmic temperature difference in the fire-tube.

3. Results

The temperature measurement results of heated water at the high-temperature section inlet and outlet, combustion products at the outlet of the high-temperature section and the boiler, and also temperature calculation results of the combustion products at the furnace outlet with different natural gas flow rates can be found in Table 3.

Table 3. Heat transfer agent values at different natural gas flow rates.

Parameter name	Parameter value						
Natural gas flow rate, m^3/s	11.00	13.00	15.00	15.90	19.63	22.02	23.28
Water temperature, $^{\circ}C$:							
at high-temperature section inlet	50	53	58	58	57	61	62
at high-temperature section outlet	70	74	88	87	77	93	92
Combustion products temperature, $^{\circ}C$, at the exit from:							
boiler	20	22	40	40	35	42	40
high-temperature section	177	227	252	279	302	332	336
furnace	758	804	841	859	913	942	959

Also, Figure 3 presents the results of the combustion product temperature determination.

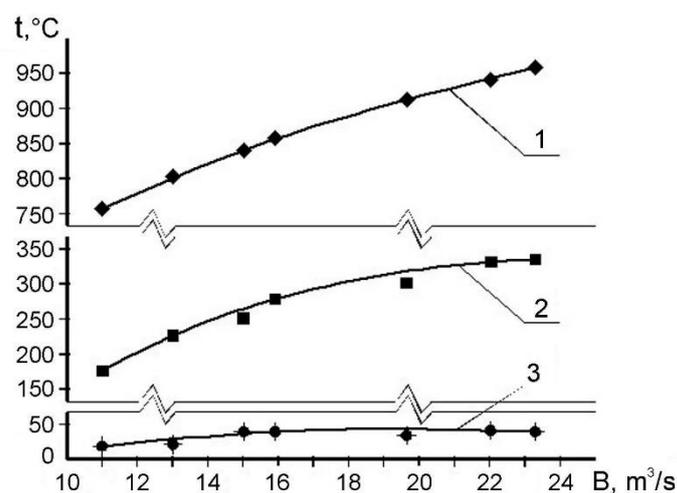


Figure 3. Temperature values of the combustion products at the boiler's measuring points: 1 – at the furnace outlet; 2 – at the high-temperature section outlet; 3 – at the boiler outlet.

Figure 4 presents the calculation results which allow to evaluate values change of the amount of heat, that gets transferred per unit time by combustion products to the heated water in the boiler's high-temperature section elements, and also in the high-temperature section taken as a whole, at different natural gas flow rates.

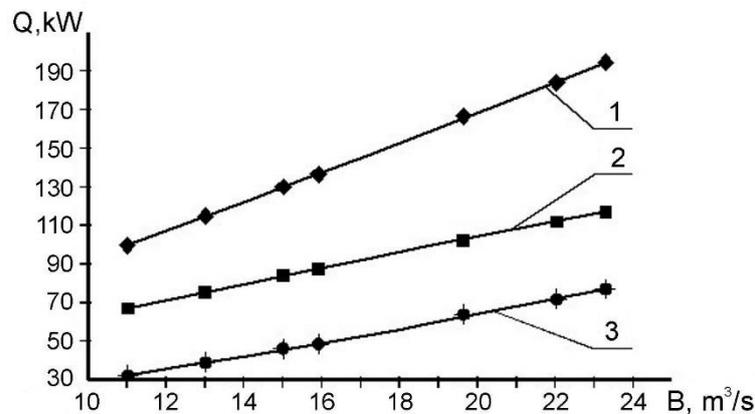


Figure 4. Amount of heat transferred from the combustion products to the heated water: 1 – total in boiler's high-temperature section; 2 – in fire-tubes; 3 – in flue-tubes.

Figure 5 presents the heat transfer coefficient values in fire-tube and flue-tube at different flow rate values of natural gas delivered into the boiler's furnace, which were determined by calculations using the mentioned-above method.

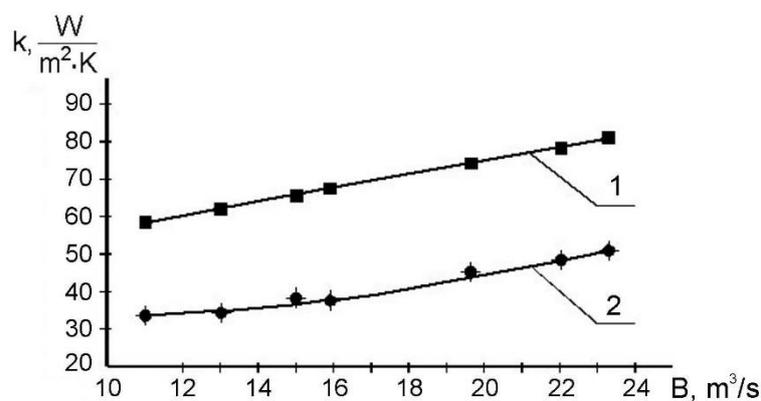


Figure 5. Heat transfer coefficient: 1 – in fire-tube; 2 – in flue-tube.

4. Discussion

The measurement results of the heated water temperature at the inlet and outlet of condensing high-temperature boiler show that considered boiler provides heat transfer agent parameters that consumer needs when its load is 50-100% from the nominal.

The combustion product temperature at the boiler's high-temperature section outlet far exceeds combustion product temperature at the outlet of a traditional fire-tube and flue-tube type water heating boilers, which don't have a condensation of water vapors, that are part of the combustion products [15, 16]. This specifies an increased value of the mean temperature difference of the heat transfer agents on the heating surfaces. Therefore, on the condition of the same heat production, the heat transfer surface of the considered condensing boiler type is substantially smaller than heating surfaces in the traditional water heating boilers. This allows substantial decrease, in comparison with the analogs, of metal consumption in the considered boiler.

At the same time, combustion products temperature at the outlet of condensing water heating boiler, due to deep cooling of the gases in its contact-recuperative section, and, therefore, heat losses with flue gas are not high. However, there is a drawback, which is defined by the presented here factors, and that is a necessity to use expensive anti-corrosive materials and coating for the boiler's contact-recuperative section and also flue gas ducts and smokestack production.

The result analysis of the amount of heat calculations, which is being transferred by the combustion products to the heated water in the boiler's high-temperature section, allow to make a conclusion that the increase of boiler's load from 50% of nominal to nominal makes the total balance of the boiler's high-temperature section to decrease by a portion of heat, which gases release in the fire-tube, from 67,3% to 60,3%, and corresponding increase by a portion of heat which combustion products release in the flue-tubes.

This can be explained by several factors. Boiler's load increase creates an increase of the heat stress in furnace volume and combustion products temperature at the boiler outlet and at the flue-tube inlet, which has been confirmed by the data presented in Table 3. Due to higher temperature at the flue-tube inlets increases mean temperature difference of the heat transfer agents on this heating surface and that intensifies convective heat transfer. Also, the increase in the boiler's heat production creates an increase in the flow rate and combustion products flow speed also increase, which intensifies convective heat transfer.

The heat transfer coefficient values in the elements of the high-temperature section of condensing water heating boiler match values of this coefficient in the corresponding heating surfaces of the fire-tube and flue-tube type water heating boilers. At the same time, an increase in the boiler's load creates a more intensive increase in the heat transfer coefficient in the flue-tubes in comparison with the heat transfer coefficient in the fire-tube. This can be explained by the fact that in the flue-tubes portion of the convective heat transfer in comparison with the portion of the radiation heat transfer is much higher, while in the furnace chamber radiation heat transfer prevails.

5. Conclusion

The experimental research results processing has shown that the thermotechnical parameters values, that characterize the heat transfer intensity in the elements of condensing water heating boiler's high-temperature section, which was designed by the employees of the Belgorod State Technological University named after V.G. Shukhov, match the equivalent parameters' values that the traditional fire-tube and flue-tube type water heating boilers have. However, the ability to keep higher temperature values of the combustion products at the suggested boiler's high-temperature section outlet in comparison with the exhaust gas temperatures in the traditional boilers allows substantially reduces the size of the high-temperature section as opposed to the analogs. Because the heat transfer in the contact-recuperative section of the condensing water heating boiler proceeds much more intensive than heat transfer in the back-end surfaces of the traditional water heating boilers, its size and metal consumption are much smaller than in the analogs.

The suggested boiler, as opposed to the traditional analogs, has a weakness and that is a necessity to use for manufacture more expensive anti-corrosive materials and coating for boiler's contact-recuperative section elements and also flue gas ducts behind the boiler. However, this kind of materials are being used in any other type of heat generator or heat recovery unit of the condensing type.

The experiment results have shown that the heat transfer agent parameters, which were produced in the condensing water heating boiler, are in compliance with the standard requirements applied to the corresponding heat transfer agents. Taking into account all the above-mentioned allows to conclude that the use of the suggested boiler as a heat generator in the stand-alone systems for the heat supply of consumers with different needs is very promising.

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