Simulation of Heat Exchange in Combustion Chamber with Premix Burner

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***Abstract*—Analysis of gas boiler performance and improvement of the combustion process of hydrocarbon fuel in combustion chambers are crucial tasks. The paper presents a developed design of the cylindrical combustion chamber of the boiler. The operating principle of the chamber was described. This study aims to evaluate the influence of the geometry of the boiler chamber with premix burner on the combustion of hydrocarbon fuel and determine heat load on surfaces of the chamber and its outlet. Based on the simulation results, the heat-transfer coefficient of the external contour for cast iron and sheet steel decreases by 4.2 times when increasing the diameter from 100 to 300 mm. Reducing the diameter of the outer contour of the boiler makes it possible to significantly increase the heat loads on the surfaces of the chamber and accordingly increase the heat transfer.**

Keywords—combustion chamber, boiler, burner, natural gas, heat flow, efficiency

I. Introduction

The smart use of energy resources and the protection of the environment are among the most critical problems facing humanity. High-temperature processes are carried out in industrial furnaces and boilers (metallurgical, chemical, petrochemical, and other industries) with a low utilization rate of organic fuel (20–40 %) [1]–[3]. As a result, these industries emit gases whose temperatures sometimes exceed 1000 °C, toxic substances, fine dust of the raw materials used, and other technological waste that pollute the environment. On the other hand, it is a source of a vast amount of thermal energy that can be used efficiently, including boiler-utilizers in the process lines [4], [5]. Therefore, the utilization of wastes of different technological processes is an important task, the implementation of which is possible based on the use of their heat in boiler-utilizers or during the joint organization of technological and energy processes in power engineering units [6]–[8].

For example, equipment of this type is actively used in oil refineries, where carbon monoxide is generated during production processes [9]. This gas, burned in the boiler chambers, involves in the production process and drives the turbines. At the same time, emissions into the atmosphere become minimal. Moreover, in some industries, the combustion of wastes forms in addition to physical heat the chemical one due to burning solids particles [10]. The boiler is structurally between a conventional shell-and-tube heat exchanger and a heat-and-tube boiler. Although its original function was to cool the high-temperature exhaust gas, it performed low-pressure steam generation as a by-product.

Today, the environmental protection aspect is becoming increasingly important, the requirements for operating conditions have become increasingly stringent [11], [12]. Therefore, the production of secondary energy resources has become an integral part of any new or reconstructed project.

One of the main requirements for modern combustion chambers is high efficiency. Therefore, minimizing heat losses during hydrocarbon fuel combustion in the chambers is necessary. In general, heat losses can be divided into three types [13]:

- Heat losses due to the chemical insufficiency of fuel combustion result from the lack of air, poor mixing in the gas burner, and a sharp decrease in the temperature at the combustion zone.
- Heat loss to the environment is caused by a significant temperature difference between the outer walls of the unit and the ambient air.
- Heat loss with exhaust gases increases with the temperature of the exhaust gases and the excess air coefficient in the combustion products.

The following ways can significantly decrease heat losses caused by chemical insufficiency of fuel combustion and thermal losses into the environment: reaching an optimal value of excess air coefficient in the combustion chamber for the elimination of air deficiency during fuel combustion, improvement of mixing of oxidizer and carbohydrate fuel, increase of insulation layer of different parts for the combustion chamber. The temperature of some combustion products can reach 1200–1700 °C and higher. It is essential to reduce the temperature of the exhaust gases to a reasonable range to reduce heat loss. As a rule, water is used as a coolant since it has a large heat capacity. Improving the quality of the combustion processes of carbon fuel in the combustion chambers to increase their efficiency is relevant and of great interest [14]–[16].

We developed a cylindrical combustion chamber of the gas boiler, consisting of the Polidoro Premix burner and the boiler's external contour for the heating carrier. The combustion chamber works as follows (Fig. 1). When the hydrocarbon fuel is burned using device 1, the heat flow with the combustion products carries to the combustion chamber's outlet by convection. Most heat is transferred to the outer wall of chamber 2, so when the heating carrier flows in the external contour of boiler 3, it heats through the wall, separating them.

This study aims to evaluate the influence of the geometrical sizes of the boiler chamber with premix burner on the combustion of hydrocarbon fuel and determine heat load on surfaces of the chamber and its outlet.

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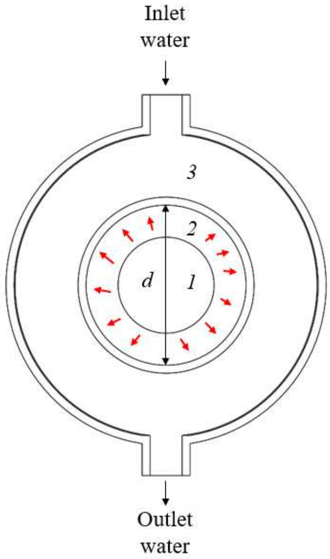

Fig. 1. Hydrocarbon fuel combustion chamber of boiler with premix burner (side view): 1 – burner; 2 – combustion chamber; 3 – external contour of the boiler.

II. Objects and Methods

For numerical simulations, the three-dimensional model of the combustion chamber of the 50-kW boiler was created. During simulations, the following geometrical sizes were set. A burner was 60 mm in diameter and 600 mm in length, with the boiler's external contour 600 mm in length. The diameter of the external contour *d* varied during calculations from 100 to 300 mm (Fig. 2).

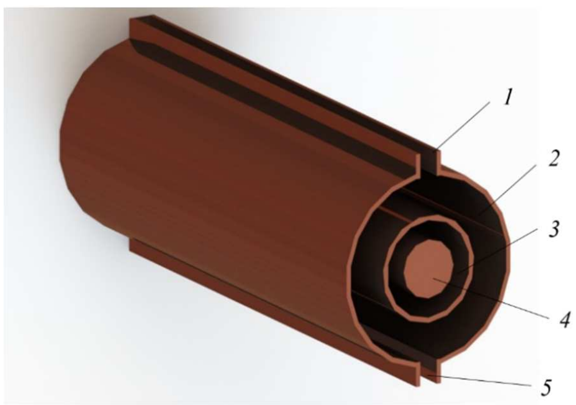

Fig. 2. 3D model of hydrocarbon fuel combustion chamber of the boiler with premix burner: 1 – water inlet; 2 – movement area of heating carrier; 3 – movement area of gas; 4 – burner; 5 – water outlet.

A calculation of hydrocarbon fuel combustion was performed using the ANSYS Fluent with the following options: finite element method, SST *k-ω* turbulence model, Finite Rate Chemistry (FRC) and Eddy Dissipation models. The advantages of the *k-ω* model are the high accuracy of estimating near-wall turbulence and sensitivity to boundary conditions in the external flow. The FRC model makes it possible to calculate reaction rates that are described by molecular interactions between liquid components.

Partial differential equations (Navier-Stokes equation) was used for numerical calculations as

$$\frac{\partial \vec{v}}{\partial t} = -(\vec{v}\cdot\nabla)\vec{v} + \nu\Delta\vec{v} - \frac{1}{\rho}\nabla p + \vec{f} \quad (1)$$

where ∇ is nabla; Δ is vector Laplacian; t is time, s; ν is kinematic viscosity coefficient, m^2/s; ρ is density, kg/m^3; p is pressure, Pa; $\vec{v}$ is velocity vector field; $\vec{f}$ is vector field of mass forces.

The Navier-Stokes equation is combined with the continuity equation in the form of

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\vec{v}) = 0 \quad (2)$$

The standard model SST *k-ω* is based on the kinetic turbulence transfer equation *k* and the specific dissipation rate *ω*, which calculated from the following equations:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k v_i) = = \frac{\partial}{\partial x_j}\left(\Gamma_k \frac{\partial k}{\partial x_j}\right) + G_k - Y_k + S_k \quad (3)$$

$$\frac{\partial}{\partial t}(\rho w) + \frac{\partial}{\partial x_i}(\rho w u_i) = = \frac{\partial}{\partial x_j}\left(\Gamma_\omega \frac{\partial w}{\partial x_j}\right) + G_\omega - Y_\omega + D_\omega + S_\omega \quad (4)$$

where G_k is the generation of the turbulence kinetic energy by averaged flow gradients; G_ω is the generation by ω-parameter; Γ_k, Γ_ω are dispersion intensity for *k* and *ω*, respectively; Y_k, Y_ω are the turbulent dissipations for *k* и *ω*, respectively; D_ω is the transverse diffusion; S_k, S_ω are the source terms.

As boundary conditions, the mass flow of hydrocarbon fuel was $G = 0.00313$ kg/s, which was determined for the boiler with the power of 50 kW and the ambient pressure at the outlet of the combustion chamber of 10^5 Pa. Natural gas was used as the hydrocarbon fuel. The composition by volume of gas was set on reference data: CH_4 – 95.50 %, C_2H_6 – 0.80 %, C_3H_8 – 0.40 %, C_4H_{10} – 0.08 %, CO_2 – 0.22 %, N_2 – 3.00 %. During combustion of natural gas in the boiler chamber at a temperature of $T = 2000$ K, the composition of combustion gases was calculated: CO_2 – 33.30%, H_20 – 65.70%, N_2 – 0.01%.

Various surfaces of radiation heat exchange (cast iron and sheet steel) were used for the comparative analysis of the heat load of the combustion chamber. The degree of cast iron and sheet steel's blackness was defined depending on heating temperature. For simplification of the mathematical model, we did not consider heat losses to the environment, and the external wall of the combustion chamber was isentropic. The main assumption at numerical calculation is that working fluids (air and combustion products) represent the mix of components with ideal gas properties and invariable thermodynamic properties depending on temperature. The initial water temperature was set at 60 ºC.

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III. Results and Discussion

The results shown in Fig. 3–7 revealed that an increase in diameter of the external contour leads to a decrease of radiation and the total amount of heat, therefore, and to decrease of efficiency of the boiler. It is caused by the increase in the area of the design which it is necessary to heat.

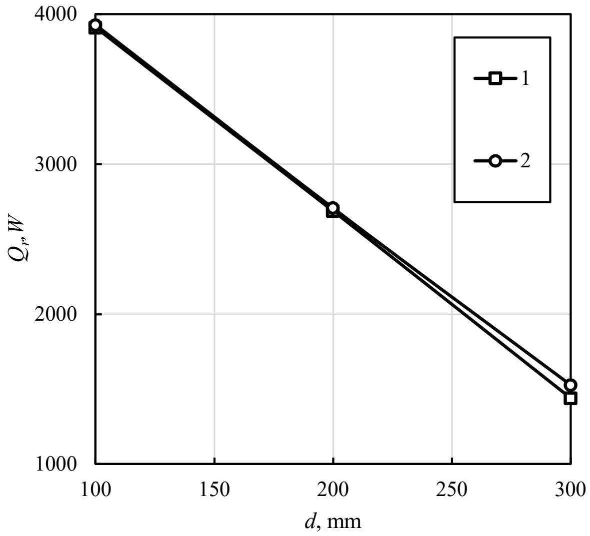

Fig. 3. Dependence of radiation flow Q_r on the diameter of external contour d, 1 – cast iron, 2 – sheet steel.

Due to an almost equal degree of blackness for cast iron (0.91) and sheet steel (0.87) in the study, indicators of a radiation flow on the external contour are also almost identical. When increasing the diameter of the external contour, the radiation heat decreases linearly. Moreover, with each increase of d by 100 mm to the external contour of the boiler, the radiation flow decreases on average by 53% for both materials under study.

Fig. 4 shows a change of the total heat flow, including all types of heat exchange during an increase in diameter of the external contour.

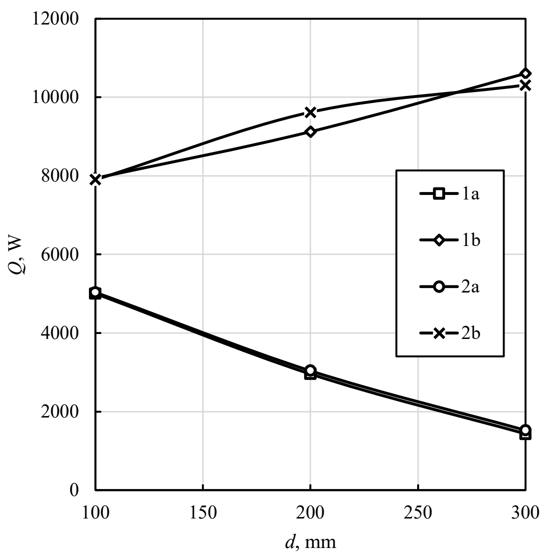

Fig. 4. Dependence of the total heat flow Q on the diameter of the external contour d; *1a, 1b* – values on the surface of the external contour of cast iron and sheet steel, respectively; *2a, 2b* – values at the outlet of the combustion chamber made of cast iron and sheet steel, respectively.

Values of the total heat flow and radiation heat flow correspondingly during the increase in the diameter of the boiler's external contour decrease for both materials under study. However, the total heat flow at the chamber outlet is inverse to the radiation heat flow. It is caused by the increased area of the combustion chamber, particularly the distance between the burner and the external contour of the boiler.

At great values of the external contour diameter, a part of the total heat flow does not have time to reach the surface of the external contour, dissipating in the direction to the outlet of the boiler. At $d = 200$ mm, the total heat flow at the combustion chamber outlet made of sheet steel was higher by 6% than cast iron.

At $d > 200$ mm, the slowdown in the growth of the total heat flow occurs at the combustion chamber outlet (Fig. 4). It is clear in Fig. 5 with the change of the external contour temperature of the boiler and temperature at the outlet of the boiler from the diameter of the external contour. When the boiler's external contour diameter is less than 200 mm, as mentioned earlier, due to the increased surface area, a part of the heat flow does not reach the wall surface of the external contour and carries it away to the device outlet. But at higher values of the diameter, in this case at $d > 200$ mm, the heat flow rate increases to the outlet because of the enlarged area of the combustion chamber.

Apparently, on *1a* and *1b* lines, the temperature of surfaces of the external contour drops rapidly but manages to be distributed on the total area before discharging the combustion chamber, resulting in a decrease of temperature on the boiler outlet.

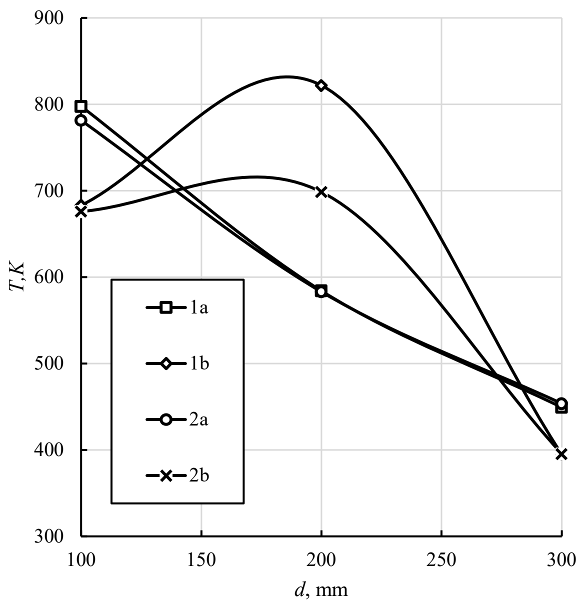

Fig. 5. Dependence of temperature T on the diameter of the external contour d; *1a, 1b* – values on the surface of the external contour of cast iron and sheet steel, respectively; *2a, 2b* - values at the outlet of the combustion chamber made of cast iron and sheet steel, respectively.

One of the main requirements imposed on gas boilers is high values of a heat-transfer coefficient from the external contour. Fig. 6 indicates the dependence of the heat-transfer coefficient of the external contour surface on the boiler's diameter.

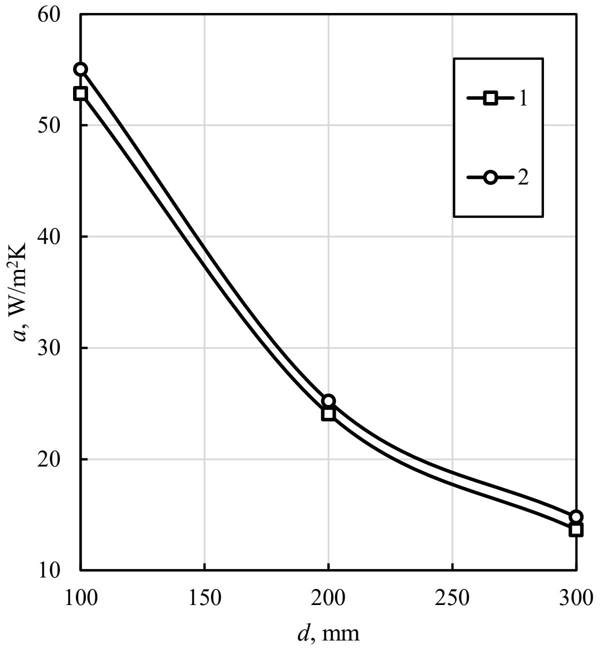

Fig. 6. Dependence of the heat-transfer coefficient α on the diameter of the external contour d for different materials: 1 – cast iron, 2 – sheet steel.

The heat-transfer coefficient of the external contour for cast iron and sheet steel decreases by 4.2 times when increasing the diameter d from 100 to 300 mm. This fact significantly negatively reflects on the efficiency of the boiler.

The total enthalpy of combustion gases also tends to decrease in the case of increasing the diameter of the external contour of the combustion chamber (Fig. 7).

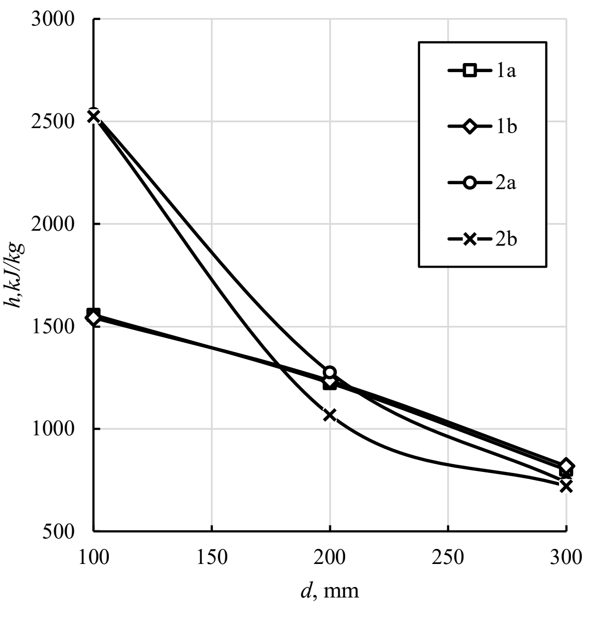

Fig. 7. Dependence of the total enthalpy h on the diameter of the external contour d, *1a, 1b* – values on the surface of the external contour of cast iron and sheet steel, respectively; *2a, 2b* – values at the outlet of the combustion chamber made of cast iron and sheet steel, respectively.

IV. Conclusion

The developed design of the boiler combustion chamber provides high values of the heat-transfer coefficient. The coefficient of the external contour for cast iron and sheet steel decreases by 4.2 times when increasing the diameter from 100 to 300 mm. With an increase in the diameter of the external contour by 100 mm, the radiation flow decreases on average by 53% for both materials under study. Therefore, it is necessary to minimize the distance between the burner and the external contour of the boiler to develop an efficient combustion chamber for the power device.

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