Intensification of heat-exchange of a direct-flow steam boiler of a coil type based on an educational laboratory stand

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Abstract. In the work under consideration, using an experimental stand formed by a cylindrical coil, the modes of air movement through the flue of a ramjet steam boiler were investigated. Experimental studies have revealed shortcomings in the operation of a direct-flow steam boiler and proposed ways to increase heat transfer in a steam boiler by turbulizing the gas-air flow in the convective part of the boiler flue. The Ansys programmable engineering environment was used to simulate the heat exchange between waste gases and water in the heat exchanger. The Ansys SpaceClaim program was used to design the geometric model. Finite element grid was created using the Ansys Icem CFD program. In the process of creation, materials were selected and designated for each part of the model, water and steam temperatures inside the heat exchanger, exhaust gas temperature, boundary conditions and heat exchange conditions between them were also set. After entering all the parameters the model calculations were carried out and the results were presented in the form of a temperature distribution diagram. In conclusion, a variant of further research of aerodynamic processes in a ramjet steam boiler and a demonstration of the selected option were presented.

1 Introduction

The direct-flow boiler is used to produce saturated steam for production needs (Figure 1). The furnace chamber is formed by an internal cylindrical coil. The coils of the coil, arranged vertically and horizontally, also form flues.

The fan pumps air into the annular gap, which is formed by the casing. By cooling the outer and inner shells, the air simultaneously heats up, enters the furnace space, and stabilizes the combustion. Air cooling of the annular flow eliminates the need to close the convective flue channel of the boiler.

Feed water enters the automatic water treatment plant, where it is softened to prevent scale formation on the boiler's heating surfaces. The softened water enters the storage tank,

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where phosphates and hydrazine are added to prevent corrosion of the heating surfaces inside the boiler [1].
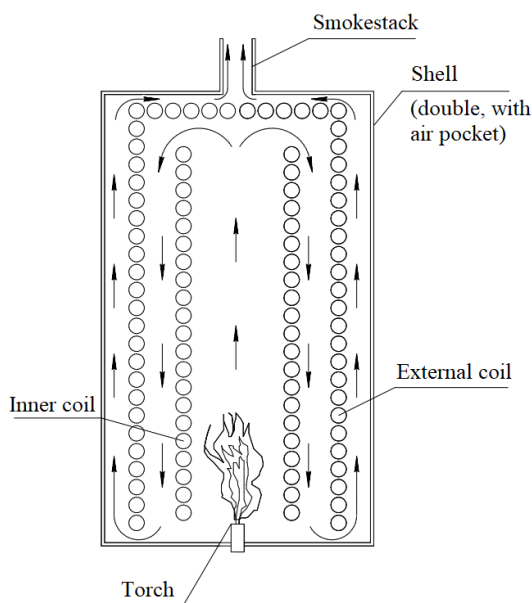
Fig. 1. Schematic diagram of a direct-flow boiler.

Condensate from steam consumers also enters the flow tank, forming feed water. Feed water comes from the tank through a filter to the suction of the feed water pump. The feed water pump discharge line is equipped with a backflow prevention valve and a bypass valve installed in series. The feed water pump supplies water to the boiler coil section.

The fuel pump supplies fuel to two injectors. Two electromagnetic valves are installed in the fuel line to regulate the boiler power. The fuel is ignited by an electric spark from the ignition system. The flow of excess air in the boiler is regulated by a throttle controlled by an electromagnetic valve located in the duct between the fan and the boiler when the boiler operates in two modes [2].

During the combustion of fuel in the furnace space, the water passing through the coil is heated, and saturated steam is obtained, which is distributed to consumers through the steam collector.

Due to their compactness, steam direct-flow boilers of the coil type are used in transportable boiler installations at oilfield sites. In the consumer services and light industry, steam boilers are used for processing and dyeing fabrics, creating knitted fabrics and products from them, as well as for drying, ironing and steaming.

These boilers are used in the production of paper products containing recycled raw materials. Steam boilers are often used directly in the production of building materials and paving slabs, as well as for heating open areas and construction sites.[3]

The laboratory stand (Figure 2) used for the study is a simplified copy of the boiler described above. The cylinder with a coil inside is located on a metal table, and includes a monoblock, which is a cylindrical metal container (diameter 368 mm, height 625 mm) with a coaxed coil (diameter 302 mm, height 563 mm), a pump, a 0.04 m^3 feed water tank, control cabinet with the possibility of automatic regulation, control and measuring fittings.

The liquid is pumped from the filled water tank into a spiral coil. The circuit closes and the water returns to the tank. The measuring part of the stand allows you to register fluid

flow parameters on the flow meter display or transmit them to a PC using the software. The water temperature is measured by a thermometer before adding water to the tank.
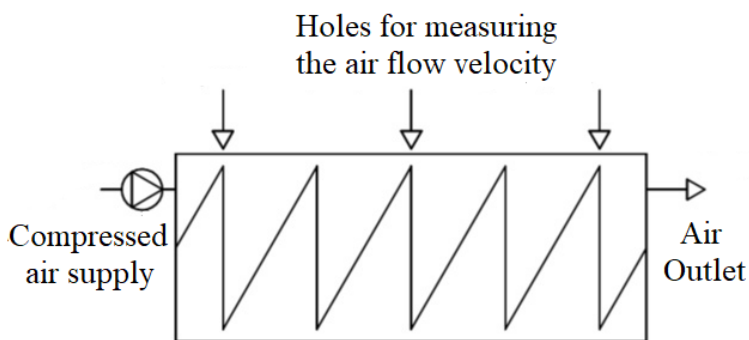
Fig. 2. Diagram of the laboratory stand.

Compressed air is supplied through a channel in the cylinder cover. Initially, the air passes through the channel, and then exits from the other side of the cylinder through the same hole in the second cylinder cover. With the help of a coaxial coil, aerodynamic drag is created inside the cylinder, due to which a vortex air flow is formed [4-5].

Through four special holes along the course of the airflow, the speed was measured and it was found that the value of Re decreases as the airflow passes through the gas chamber. This is due to the aerodynamic drag in the flue formed by the coil [6].

Thus, at the outlet of the last flue, there is a loss of turbulence of the gas flow, therefore there is no intensive heat exchange with the walls of the coil and the air flows out of the extreme opening because, at the same time, the temperature of the gases remains relatively high. In other words, the heat that can be used to reheat water through the walls of the coil simply came out through the extreme opening, therefore the quality of heat exchange decreases. Experimental data are given in Table 1.

Table 1. Font styles for a reference.

	Place of measure-ment	Gas velocity, m/s	Time, sec	Air temperature, C	Kinetic viscosity, m²/s	Re
Measurement 1	The beginning	1.53	60	22.4	$15.2856 \cdot 10^{-6}$	36 033.9
Measurement 2	Centre of the cylinder	1.09	60	22.0	$15.2481 \cdot 10^{-6}$	25 734.4
Measurement 3	The end	0.87	60	21.6	$15.2104 \cdot 10^{-6}$	20 591.2
Measurement 4	Gas output	0.41	60	21.3	$15.1822 \cdot 10^{-6}$	9 721.9

It is proposed to increase the heat exchange due to the modernization of the laboratory installation by turbulizing the gas flow.

Turbulators (Figure 3) are used to increase the time of heat transfer from the incandescent flue gases to the coolant. Thus, the efficiency of heat transfer is significantly increased. The efficiency of the boiler is also increased.

The special design of the turbulator is arranged in such a way that the laminar gas flow is pressed against the surface of the heat exchanger wall. Due to its use in harsh operating conditions, the designs of turbulators are subject to significant wear.
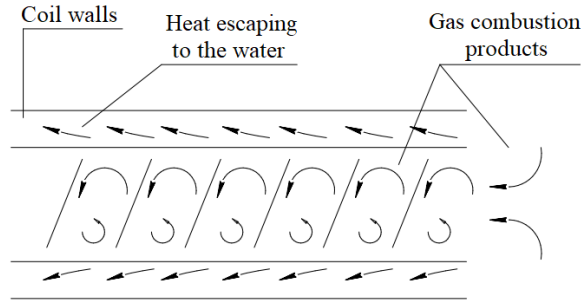
**Fig. 3.** The principle of operation of the turbulator.

2 Materials and methods

When modelling the heat exchange between flue gases and water in the coil, the Ansys programmable engineering environment was used.

The first step in the design was the creation of a geometric model of a laboratory stand simulating a furnace chamber of a steam boiler of a coil type. Two variations of it were created, in one the turbulators were fully modelled, and for the other, they were not provided. As part of the creation of these models, it was assumed that the flame phase has a fixed size and temperature at each of its points. A field of reverse velocities was also created to simulate atmospheric air. The Ansys SpaceClaim program was used in the design.

The next stage was the creation of a finite element grid using the Ansys Icem CFD program on top of already created geometric models. During the creation, materials were selected and designated for each part of the model. The water and steam temperatures inside the coil, flue gas temperatures, boundary conditions, and the conditions of heat exchange that occur between them were also set.

After the introduction of all the parameters required for the solution, the calculation of the model was launched, the results of which are presented in the form of a temperature distribution scheme (Figures 4 and 5) [7].
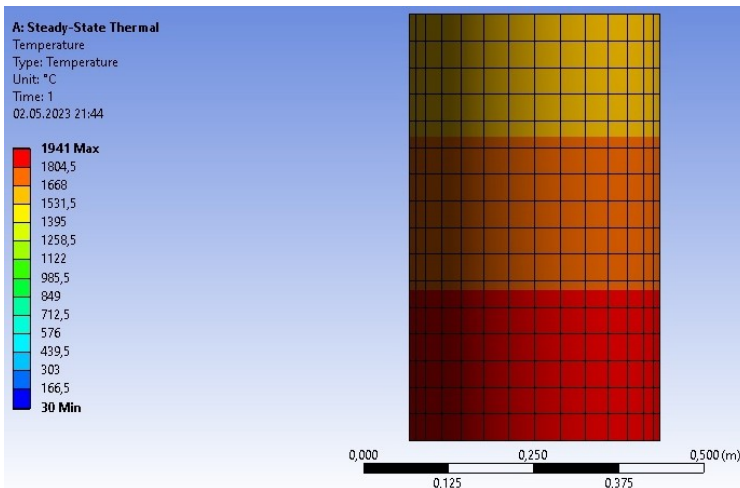

Fig. 4. Temperature distribution scheme without modification.

This design makes it possible to accelerate the gas flow in the central gas furnace of the test bench by 0.14 m /s, which increases the temperature of the heated medium but increases fuel consumption, since the gas temperature at the outlet of the gas furnace increases, and the use efficiency of the heat generated decreases. At the same time, reducing the angle of inclination of the turbulator arc will reduce fuel consumption, increase the useful efficiency of the heat generated, improve vortex formation and reduce the uniformity of the flow, but at the same time the gas flow rate inside the furnace will decrease, heat loss through the brickwork will increase and even the heat exchange process will be disrupted with excessive deceleration.[8]
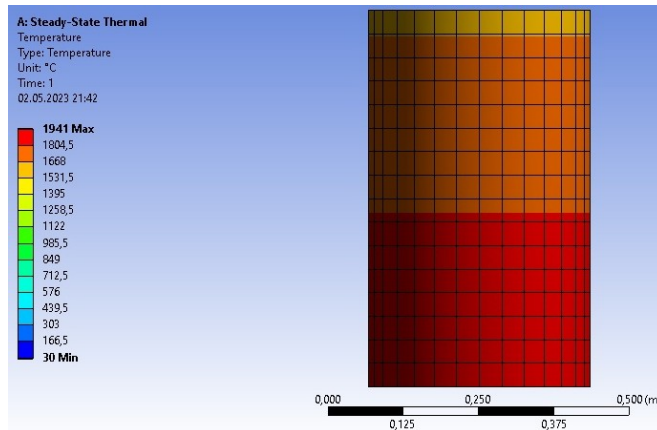
Fig. 5. Temperature distribution scheme with the set modifier.

With this modification, the flows bordering the coil through the hole continue their movement, and the flows that are distant and inefficient slide into the space between the coils, changing the parameters of vorticity, uniformity and gas flow velocity (Figure 6).
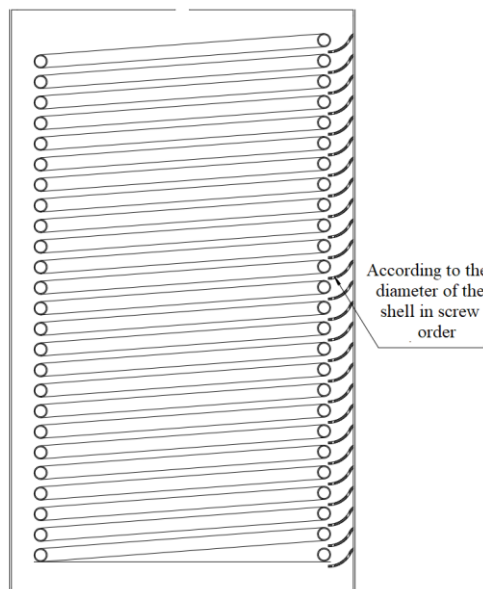
Fig. 6. The proposed layout of the turbulator blades.

In the course of laboratory work, as well as process modelling in the Ansys environment, it was revealed that only those flows bordering the coil are max-imally affected in the flue, however, the central flows have less efficiency, therefore, it was decided to install turbulator blades on the inner surface of the boiler in diameter in a screw order with a hole closer to the coil.

To assess the overall effect of turbulators-blades installed on the inner surface of the boiler wall, it is necessary to have information on several parameters, first of all, the gas flow rate in the space between the coil and the wall. This criterion, in turn, also depends on a large number of parameters, and therefore the calculation of the flow rate is extremely complex and is often derived from computer modelling of the process. However, its most approximate value can be obtained using the modified formula of Bernoulli's law, the final form of which for a gas medium looks as follows [8].

$$v_1 = \sqrt{\left(\frac{p_1}{y_2} + \frac{v_2^2}{2g} + h_w - \frac{p_1}{y_1}\right) \cdot 2g} \qquad (1)$$

This formula made it possible to calculate the average flow rate of exhaust gases equal to $v=0.99$ m/s, approximately corresponding to the speed obtained during laboratory testing of the stand at lower temperatures and modified gas composition.[9]

$$v = \frac{v_0^2}{R} \cdot t + v_0 \qquad (1)$$

To solve this problem, the values of the gas temperatures at the outlet of the flue furnace before and after modification were determined. Table 2 summarizes the main formulas used in the calculation.

When performing the thermal calculation of the flue, the following initial data were taken (Table 2):

Table 2. Initial data.

Parameter name	Designation	Value	Unit of measurement
Boiler steam capacity	D	1	t/h
		0.278	kg/s
Steam pressure at the boiler outlet	P	0.78	MPa
Feed water temperature	t_{fw}	30	°C
The temperature of the sucked air	t_{sa}	40	°C
Type of fuel	Diesel		
Boiler length	L_K	0.625	m
Boiler diameter (with insulation)	D_K	0.386	m

The main formulas of the performed thermal calculation are presented in Table 3. The necessary data obtained were the gas velocity and temperature at the outlet of the furnace.

Where α – is the air flow coefficient, $V0$ – is the theoretical volume of the air, B – is the fuel consumption, Tf – the effective temperature of the furnace, Fsec – is the cross–sectional area of the furnace, $F\sum$ - the total heating area, φ – the coefficient of heat conservation. [10]

Table 3. Thermal calculation of the flue.

Parameter name	Designation	Value before modification	Value after modification	Formula
Gas velocity in the furnace, m/s	$\tilde{\omega}$	1.45	1.59	$\dfrac{\dfrac{\alpha \cdot V_0 \cdot B \cdot 0{,}1 \cdot T_f}{(273 \cdot 1{,}47)}}{F_{sec}}$
The temperature at the beginning in the furnace flues, $^{\circ}$C	t	1941		Accepted according to the enthalpy table
Temperature at the outlet of the flue furnace, $^{\circ}$C	T	1560	1649	$\left(\dfrac{\upsilon_a}{m \cdot \left(\dfrac{5{,}67 \cdot \varphi_{med} \cdot F_\Sigma \cdot \alpha_T \cdot T_d^3}{\left(10^{11} \cdot \varphi \cdot B_p \cdot V_{med}^c - 273\right)} \right)^{0{,}6}} \right) + 1$

3 Results and Discussion

The conducted research using thermal, mechanical and hydro-gas-dynamic calculations showed that the greatest effect, which this study is aimed at, was given by turbulators of the blade with an arc bending angle of 180 degrees. This design made it possible to accelerate the gas flow in the central flue-furnace of the laboratory stand by 0.14 m/s, which will increase the temperature of the heated medium, but at the same time, fuel consumption will in-crease, since the temperature of gases at the outlet of the flue-furnace will in-crease, the use efficiency of the consumption of the released heat will decrease. At the same time, reducing the arc angle of the turbulator will reduce fuel consumption, increase the efficiency of using the released heat, improve vorticity and reduce the uniformity of the flow, but at the same time the gas flow rate in the furnace will be reduced, which will lead to an increase in heat loss through the brickwork, and in case of excessive deceleration, completely disrupt the heat exchange process. Critically, the minimum speed is achieved already at the bending angle of the turbulators of 90 degrees. In further studies of this modernization, as well as in its application in real snake-type boilers, it is necessary to establish the optimal radius and angle of the blade bending arc.

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