Investigation of the distribution of heat fluxes in the combustion chamber of a hydrogen-oxygen steam generator

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Abstract. The article presents the results of experimental studies of thermal processes in combustion and evaporation chambers of an experimental hydrogen-oxygen steam generator with a thermal capacity up to 25 MW developed at the Joint Institute for High Temperatures of the Russian Academy of Sciences (JIHT RAS). The studies have shown that the design of the mixing element has a significant effect on the heat fluxes in the combustion chamber. The effect of several designs on heat fluxes near the fire wall and on the completeness of the combustion of hydrogen in oxygen have been investigated experimentally. The result of experimental study of thermal processes in a hydrogen-oxygen-steam generator with a thermal capacity of up to 25 MW allowed estimating the real heat fluxes and correction factors for the calculations.

Introduction
The use of hydrogen-oxygen generation of water steam to overheat steam of stationary steam turbines for increasing their efficiency and maneuverability is considered in [1-6]. However, the creation of such generators requires solving a number of problems, e.g., to ensure the reliable cooling and high completeness of hydrogen combustion in oxygen [7, 8].

The study of thermal processes in heat-stressed structures is an important task, since it avoids excess in the limiting temperature and loss of its strength, provides an optimal coolant flow and reduces heat losses. For hydrogen-oxygen steam generators, this problem is especially important.

During stoichiometric combustion of hydrogen in oxygen and pressure up to 7 MPa, the temperature in the combustion chamber can reach 3600 K, and the heat flux reaches 15 MW/m², while the cooling water flow must be minimal, since it is fed into the structure and lowers the temperature of the generated steam. Basing on the experience of rocket engine development [2, 9, 10], in order to provide the above conditions, a complex cooling was used in the combustion chamber. It included external cooling of the fire wall and internal wall surface water jets for a reliable cooling at a thermal capacity of 25 MW to be ensured by a water flow of 2.7-2.8 kg/s at the total of 4.2-4.8 kg/s [11]. Besides the cooling water flow and the heat output of the hydrogen-oxygen steam generator are non-linear, which requires the creation of an appropriate control system.

As it has been found in [9], the design of the mixing element significantly influences the heat fluxes and, if the combustion front is not removed from the firing bottom, it inevitably melts, even at a short-time operation, decreasing the life-cycle of the installation. In this connection, mixing elements with different configurations of the fire bottom were developed, which allowed complete elimination of the meltback and conduct long-term launches.
1. The method for calculations and for experimental research of a hydrogen-oxygen steam generator with a thermal capacity up to 25 MW

1.1. Combustion chamber

The scheme for calculations and experiments is shown in Figure 1. The inner wall of the combustion chamber of the steam generator is a finned bronze cylinder with a length of 190 mm and a narrowing at 50 mm from the outlet.

Cooling water is supplied from outside along the finned surface at a flow rate of 2.1-3.5 kg/s (depending on the heat output). This ensures that the wall temperature does not exceed 600-650 K. Inside, from the holes in the mixing element, along the wall of the combustion chamber jets of water are fed at a flow rate of 0.3-0.5 kg/s, forming a water film on the inner wall that additionally protects it from high-temperature flue gas streams. The calculation of the water flow rate for film cooling was carried out in accordance with Ilevlev's method [10] because of the necessity of film extension along the entire length of the combustion chamber, which is confirmed by the results of the experiment. During the experimental studies, measurements were carried out for the flow rate, pressure and temperature of the inlet water and outlet temperature, the pressure in the combustion chamber, and the temperature of the water steam after mixing it with cooling water. The water heating was measured only on a cylindrical section, which is explained by the design difficulties of installing a temperature sensor at the outlet of the nozzle.

The calculation of heat transfer in the combustion chamber is rather complicated, since it involves the non-stationary and non-uniform combustion and mixing of the fuel components, evaporation of the near-wall layer of water and the absorption of radiation from the combustion products. Therefore, the average coefficient of heat transfer from combustion products to water was estimated only on the basis of experimental data. The main criterion for the calculation was the heat flux value, determined by the flow rate of the cooling water and the change in temperature at the inlet and outlet of the combustion chamber.

The following assumptions were made for calculations:

- the heat flow and temperature of the fire wall are constant over the entire length of the cylindrical part of the combustion chamber, which corresponds to the methods for calculating liquid rocket engines;
- increase of the temperature of the cooling water along the length of the cylindrical part of the combustion chamber occurs linearly.

1.2. Mixing chamber

The main differences between the mixing chamber and the combustion chamber are:

- no tapering nozzle at the outlet;
- no additional inlet water cooling;
- a significantly lower temperature of the steam (1300-1700 K);
- the cooled wall is made of stainless steel AISI 321.
Scheme for computational and experimental studies of thermal processes in the mixing chamber of a hydrogen-oxygen steam generator with a thermal capacity up to 25 MW is shown in Figure 2.

Figure 2. Scheme for performing computational and experimental studies of thermal processes in the mixing chamber of the hydrogen-oxygen steam generator with a thermal capacity up to 25 MW: TS1 - a temperature sensor for the cooling water at the inlet to the mixing chamber, TS2 - a temperature sensor for the cooling water at the outlet, TS3 - temperature sensor for combustion products, PS - pressure sensor inside the evaporation chamber.

The method of calculation for the mixing chamber is similar to the calculation procedure for a combustion chamber.

1.3. Mixing units
Mixing elements in the hydrogen-oxygen steam generator are used for mixing hydrogen and oxygen and ensure the most complete possible reaction of the components. Water is also supplied through the jets in the fire wall for the internal wall-mounted cooling of the combustion chamber.

Since the firewall is in direct contact with high temperature combustion products, the determination of the effect of heat fluxes on it is extremely important, since the entire installation reliability directly depends on it.

To study the influence of the geometry of the mixing element on the value of the heat flux on its fire wall, three types of mixing elements with the angles of the hydrogen jets intersection of 15° and 0° have been developed and manufactured, providing different distances of the combustion front from the firing bottom and the ratio of the pulses of hydrogen and oxygen jets.

The evaluation of the heat flux was carried out based on the results of inspection of the fire walls of the mixing element and the combustion chamber after experimental studies.

2. Results of calculations and experimental studies for the hydrogen-oxygen steam generator with a thermal capacity up to 25 MW

2.1. Combustion chamber
To study the thermal processes in the combustion chamber of the hydrogen-oxygen steam generator with a thermal capacity up to 25 MW, 2 fire tests were carried out at various thermal powers (from 8.5 to 16 MW) and pressures (from 3 to 5 MPa). In Figure 3 and Figure 4 the results of the combustion chamber tests are shown.
Figure 3. The experimental results of a hydrogen-oxygen steam generator at a thermal capacity of 8.5 MW, a pressure of 3 MPa and a cooling water consumption of 1.8 kg/s:
1 – thermal capacity of the steam generator, MW; 2 – increase of the cooling water temperature; 3 – heat flow on the wall of the combustion chamber, MW/m².

Figure 4. The experimental results of a hydrogen-oxygen steam generator at a thermal capacity of 15 MW, a pressure of 5 MPa and a cooling water consumption of 3.4 kg/s:
1 – thermal capacity of the steam generator, MW; 2 – increase of the cooling water temperature; 3 – heat flow on the wall of the combustion chamber, MW/m².

In Figure 5 the results of calculating the temperature of the cooled wall from the inside and the heat transfer coefficient are shown. The temperature of cooling water during the tests was constant and amounted to 285 K.

Figure 5. The results of calculating the temperatures of the cooled wall from the inside and the average heat transfer coefficient of the combustion chamber:
1 - wall temperature at a thermal capacity of 8.5 MW, 2 - wall temperature at thermal capacity of 15 MW, 3 - heat transfer coefficient at thermal capacity of 15 MW, 4 - heat transfer coefficient at thermal capacity of 8.5 MW.

Figure 6. The temperature of the steam in the mixing chamber during the test and the results of calculating the temperature of the cooled wall from the inside and the heat transfer coefficient at a thermal capacity of 20 MW, a pressure of 7 MPa and a cooling water flow rate of 1.4 kg/s:
1 - steam temperature, 2 - wall temperature, 3 - heat transfer coefficient.

The results of measurements and calculations show that the heat fluxes to the combustion chamber wall reach 8-9 MW/m², with the thermal capacity of the hydrogen-oxygen steam generator of 15 MW, while in the narrowing region they can increase by 3-4 times [8]. Cooling with a large amount of water
allows maintaining the wall temperature of the combustion chamber on the flow side at 640-680 K, which does not exceed the melting point of the material. It is seen that with a decrease in the amount of water and an increase in the temperature of the coolant, the heat transfer coefficient decreases and the wall temperature on the liquid side is close to the boiling point. Nevertheless, it is possible to reduce more the amount of cooling water by 30-40%, while its outlet temperature will be 370-390 K.

2.2. Mixing chamber
To study the heat fluxes in the mixing chamber, one fire test was carried out at a thermal capacity of 20 MW, a pressure of 7 MPa and a cooling water flow rate of 1.4 kg/s. In Figure 6 the results of experimental and calculated studies are shown.

It can be seen from the results of the research that the heat flux in the mixing chamber reaches 6 MW/m², and the heating water is heated by almost 70 degrees, which, at a pressure of 7.5 MPa, leaves a reserve to reduce the flow to 800-900 g/s, while the wall temperature from the steam side will not exceed 900 K, which will not significantly affect the strength characteristics of the steel from which the inner wall is made.

2.3. Mixing units
The results of experimental studies of mixing units have shown that the greatest influence on the magnitude of the heat flux in the fire wall is the remoteness of the combustion front and the vortex flows that are formed when hydrogen and oxygen flow out of the jets. Figure 7 shows the fire walls of mixing elements with the angles of the hydrogen jets intersection of 15° and 0° after tests of up to 300s long. It is apparent that there are almost no meltbacks, and they are totally absent on the 0° mixing element. It can be concluded that the heat fluxes have become smaller and the temperature of the fire walls does not exceed the melting point.

![Figure 7. Fire walls of mixing elements with angles of hydrogen jets intersection of 15° (left side) and 0° (rite side) after tests of up to 300 seconds](image)

During the tests of the mixing elements, steam was taken at the output of the hydrogen-oxygen steam generator to determine the concentration of residual hydrogen and oxygen in it. It has shown that the concentration of hydrogen at the outlet does not exceed 0.3% (vol.), and oxygen – 0.8% (vol.).

**Conclusion**
The complex of calculations and experimental studies of thermal processes in a hydrogen-oxygen steam generator with a thermal capacity up to 25 MW has shown a possible range of operating parameters that ensures high efficiency of its basic elements. Optimization of the design provides the necessary completeness of combustion of hydrogen and an output to the calculated power within a few seconds.
Acknowledgments

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