Minimization of hydrogen concentration in the superheated mixture at steam turbine working fluid overheating by mixing with high-temperature products of hydrogen in oxygen combustion at nuclear power plant

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Abstract. A new design of hydrogen-oxygen superheater with hybrid cooling of the combustion chamber with feed water and low-temperature steam is proposed for smoothening the cooling process in order to reduce the residual hydrogen content in the process steam. The combustion chamber at this design consists of two parts. In the first part, external cooling with feed water is used for smooth cooling of combustion products to 1900 ... 2100 K in the most thermally stressed zone. In the second part, low-temperature steam is used as coolant for external cooling, the temperature of the generated high-temperature steam is reduced down to 1400 ... 1500 K. Finally, the obtained high-temperature steam is mixed with the working fluid.

1. Introduction

Production of steam by burning hydrogen in oxygen can find wide application in steam turbines of big power plants, including nuclear power plants. Calculations carried out by a number of researchers show that the use of hydrogen-oxygen superheaters of megawatt power level can be effectively used to increase the maneuverability and reliability of power plants with steam turbines using both hydrocarbon [1, 2] and nuclear fuel [3–5]. One of the most important problems in this case is to minimize the concentration of unburned hydrogen in the resulting steam.

The main factor affecting the completeness of hydrogen combustion is the cooling rate of the combustion products, while a lower cooling rate provides a lower hydrogen content in the resulting steam [6]. Earlier experimental studies of the completeness of hydrogen combustion in hydrogen-oxygen steam generators, in which water cooling of the combustion chamber is used, showed that the hydrogen content in the generated steam can reach 1.5...3% depending on the design of the mixing element and pressure [7–9]. In the designs described, water after cooling the combustion chamber mixes with the combustion products, which leads to their rapid cooling. A decrease in the rate of cooling of the products of combustion of hydrogen and oxygen can be arranged by using steam as a cooling agent. Significant disadvantages of using steam are the lower cooling efficiency of the combustion chamber and the need for the steam itself with required pressure.
2. New design of the combustion chamber development

Tests carried out using combustion chambers without direct mixing of combustion products with cooling component, when the combustion products are cooled by simple heat exchange through the walls of the combustion chamber to temperatures of 1200...1500 K, showed that, the completeness of hydrogen combustion increases to 99.97%. Based on these results, a new design of a hydrogen-oxygen superheater for power plants with steam turbines was proposed (figure 1).

![Figure 1. The concept of hydrogen-oxygen superheater for power plants with steam turbines.](image)

The principle of operation of the proposed design is as follows. In the most thermally stressed part of the combustion chamber, where the process of combustion of hydrogen in oxygen takes place, external water cooling is used with feed water leaving the condensation unit, which makes it possible to ensure smooth cooling of combustion products to 1900...2100 K and reduce the hydrogen concentration to 2...4% (vol.). At the same time, the cooling water does not mix with the combustion products, but returns to the feed water circuit and then to the main steam generator. After that, the pre-cooled mixture enters the mixing chamber, which is cooled by water steam coming from the main steam generator. At the same time, in the initial section of the mixing chamber, steam is supplied in minimal quantities along the wall of the mixing chamber for its better cooling. This allows to reduce smoothly the temperature of the combustion products to 1400...1500 K and provide a hydrogen content of 0.03...0.005% (vol.). Finally, the combustion products are mixed and the required superheating of water steam from the main steam generator takes place.

3. Estimation of the hydrogen concentration in the superheated mixture

As it was mentioned above, the products of combustion of hydrogen in oxygen are used to superheat steam from the main steam generator of the power plant. It should be noted that to increase the efficiency of a steam turbine, relatively small degree of overheating is required accounting for 20...50 degrees for humid steam turbines [10]. When using hydrogen only to increase the maneuverability and reliability of the turbine, overheating is not required. Thus, the consumption of combustion products
actually depends only on the value of the required additional power, which is usually 5 ... 12% of the rated power of the turbine [2, 11]. Considering that the enthalpy of combustion products, even after preliminary external cooling with water in the combustion chamber, will be 3 ... 4 times higher than the enthalpy of the main steam, their consumption will be 1...3% of the nominal at required power increase of the turbine by 5...10%. Thus, when the combustion products are mixed with the main steam flow, hydrogen concentration in the resulting mixture is expected to be less than 0.0005% (vol.). It is obvious that such hydrogen concentrations cannot be a hazard to the operation of the steam turbine and other units of the power plant.

However, there may be a risk of hydrogen accumulation in the condenser if the volume of the working fluid is substantially reduced. Together with this, the steam entering the condenser from the turbine always contains air that enters the turbine through the end seals of the steam turbine, leaks in the flange joints of various elements, where the pressure is less than the barometric pressure, etc. Part of the air enters the condenser through the leaks in the connection of the turbine outlet pipe and condenser adapter pipe. In the condensers of steam turbines of single-circuit nuclear power plants, the content of non-condensable gases increases due to radiolysis products. If air and other non-condensable gases are not removed continuously from the volume of the condenser, then it will not be possible to create a vacuum in it. The suction of the steam-generating mixture from the steam space of the condenser is carried out by an air pump (ejector), which releases this mixture, as a rule, into the environment. Thus, the hydrogen remaining after the condensation of steam is mixed with other non-condensable gases and removed into the atmosphere, which excludes its accumulation in the flow path of the steam pipelines.

4. Conclusion
The proposed design of a hydrogen-oxygen superheater for power plants with steam turbines provides residual hydrogen content of 0.03...0.005% (vol.) before mixing with the main steam. When the combustion products are mixed with the main steam flow, the hydrogen concentration in the resulting mixture will already be less than 0.0005% (vol.), which cannot pose a danger to the operation of the steam turbine and other units of the power plant. In addition, taking into account the peculiarities of the operation of all condensing power plants, the remaining hydrogen will be mixed with other non-condensable gases and removed into the atmosphere, which excludes its accumulation in the flow path of steam pipelines. Thus, the proposed design of a hydrogen-oxygen steam superheater allows the safe hydrogen utilization at combustion to improve the efficiency, reliability and maneuverability of power plants with steam turbines.

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