Features of thermodynamic and thermal processes in hydrogen combustion units and systems on their basis

A I Schastlivtsev and V I Borzenko

Joint Institute of High Temperature, Russia, 125412 Moscow, Izhorskaya, 13, Bd. 2
h2lab@mail.ru

Abstract. The main types and designs of hydrogen combustion units (HCU), including hydrogen-oxygen steam generators, superheaters and air heaters of various power levels, are considered. The main problems arising in the development, creation and testing of such installations are determined, including the problems of cooling the most heat-stressed units, mixing of the main components of the fuel and oxidizer, mixing of high-temperature combustion products and ballasting components, problems associated with the completeness of hydrogen combustion and ensuring safety during operation.

1. Introduction

Currently, the world energy industry is undergoing a period of important structural changes, and one of the main trends is the constant growth of the annual commissioning of renewable energy sources (RES) capacities. To ensure the sustainability of power systems and guarantee the quality of power supply, the spread of RES must be supported by energy storage systems. Hydrogen is seen as an efficient and environmentally friendly secondary energy source for energy storage in the energy systems of the future. However, modern hydrogen technologies remain relatively expensive, especially in areas related to the production and use of hydrogen, and require significant government support. Meanwhile, the problem of using hydrogen in the field of high capacities can be solved by hydrogen combustion units (HCU), the technologies for the production of which are well mastered, including in Russia.

Hydrogen as a fuel for power plants has a number of important features: high combustion heat, wide concentration limits of ignition and stable combustion, high flame propagation rates (7 times higher than for methane), low activation energies during combustion in oxygen and air. For power engineering, it is of great importance that when a stoichiometric mixture of hydrogen burns in oxygen, pure superheated steam is produced - the working fluid of modern steam turbine plants. In this case, the transfer of heat from the fuel to the working fluid can be carried out most efficiently - by mixing the combustion products (superheated steam with a high temperature) with the working fluid (water or steam), i.e. with minimal losses of fuel exergy.

The technology of combustion of hydrogen in oxygen in order to obtain high-temperature steam or air, implemented in hydrogen-oxygen steam generators, superheaters and air heaters, makes it possible to create installations with a high specific power and no harmful emissions during operation. The high speed of the processes occurring in them (combustion of hydrogen, heat transfer, mixing of
components, etc.) provides a minimum start-up and recovery time, which is especially important in the case of using such technologies as backup energy sources.

2. The main types of hydrogen combustion units
Hydrogen-oxygen plants can be classified by the type of coolant used (ballasting component), by the technologies used to create the combustion chamber, and by the type of mixing of hydrogen and oxygen. By the type of ballasting component, two main types of hydrogen-oxygen plants can be distinguished:
- hydrogen-oxygen steam generators and superheaters [1-3];
- hydrogen-oxygen air heaters [4, 5].
In most cases, the ballasting component is used simultaneously to cool the walls of the combustion chamber. The type of ballasting component used determines the field of application of the HCU. When using water and steam, the final product of the HCU is superheated steam, which can then be used as a working medium for steam turbines [1, 6-8]. When using air at the outlet, air is obtained, heated to a certain temperature, which is then used as a working medium for gas turbines. [5].
By the type of technologies used to create a combustion chamber, 2 main types of HCU can also be distinguished:
- rocket technologies;
- gas turbine technologies.
Experimental models using rocket technologies were created in Russia [1, 9, 10] and Germany [8], and using gas turbine technologies in Japan [11]. The most promising for HCU are rocket technologies, since they provide a higher completeness of hydrogen combustion, are more compact, and have a shorter start-up and operating time.

3. The main problems and features of the study of thermal processes in the HCU
The use of steam from the HCU in steam turbines necessitates their high efficiency. The main losses in the HCU are associated with incomplete combustion of hydrogen and heat losses to the environment. With cooling water, up to 5...7% of the total released heat can be removed from the heat-stressed parts of the steam generator [12]. Therefore, in order to achieve high efficiency, it is necessary to use all the cooling water for steam production. This, in turn, entails the need to create such a design of the compressor station, which will provide the necessary cooling with a limited flow of water.
Ensuring reliable cooling of the most heat-intensive units of a hydrogen-oxygen steam generator is an important design problem. In particular, in [13] it is shown that usually the heat fluxes in the combustion chamber of the HCU are up to 20 MW/m².
To solve this problem, a combined system for cooling the walls of the combustion chamber is mainly used. Firstly, external cooling of the combustion chamber walls is used, which are made of heat resistant bronze, which provides high thermal conductivity, preventing the walls from heating up by more than 150 degrees. Secondly, internal cooling is used by sprinkling the wall layer with a small amount of water, which also lowers the temperature of the combustion chamber walls and ensures a longer service life. By dividing the cooling water flows into internal and external, a decrease in the concentration of steam in the combustion zone is achieved, which leads to an increase in the completeness of fuel combustion.
When steam is supplied to the flow path of steam turbines, an important requirement for its parameters is temperature irregularity, which should be no more than 15...30 degrees along the radius. This is due to the peculiarities of the rotor blades, for which a large nonuniformity of temperatures can lead to additional thermal stresses and their premature destruction. When creating an internal combustion chamber both in Russia and in Germany, it was possible to obtain an uneven temperature at the exhaust of 7...10 degrees at installations of a megawatt power level [9, 12], by mixing a high temperature flow with a large amount of cooling water.
The presence of unburned hydrogen in the generated steam is especially dangerous for the subsequent use of this steam in closed cycles of steam turbine plants. Even a small content of it (less
than 1% (vol.) Can lead to the formation of an explosive mixture in the stagnant zones of the elements of power equipment, in particular in capacitors. It is known from the experience of rocket and gas turbine engineering that in order to ensure the most complete combustion of the fuel, it is necessary to ensure its good mixing with the oxidizer. There are 2 main design options for organizing the mixing of fuel and oxidizer jets:

- Centrifugal nozzles;
- Jet nozzles (cross jet and coaxial jet).

Centrifugal nozzles have a wide and relatively short spray cone, while the spray is thinner than for jet nozzles, therefore they are most widely used when supplying fuel or an oxidizer in the form of a liquid, and since HCU mainly uses gaseous components in them, they do not will apply.

Jet nozzles are smaller and simpler than centrifugal nozzles and this allows more of them to be placed on the mixing element. For example, in the most advanced DLR mixing element [12] placed 58 coaxial nozzles on a diameter of 100 mm, which significantly complicates its design. The flow rate of jet nozzles is 2.5...3 times higher than that of centrifugal nozzles, which makes it possible to ensure their high throughput. Their main disadvantage is a relatively long range and a small spray angle, and therefore, for the best mixing, the intersection of the jets of fuel and oxidizer, or a large difference in the speeds of the components (in the case of coaxial nozzles) is used.

The advantage of such a mixing element is its reliable operation in a wide power range. But at the same time, to ensure high completeness of hydrogen combustion, a significant complication of the design is required.

The use of coaxial jet nozzles is also advisable to use in an internal combustion unit with a combustion chamber that provides additional mixing of the components due to the injection of a ballasting component into the combustion zone. However, in this case, a significant slowdown of chemical reactions in the combustion zone can occur and a decrease in the completeness of hydrogen combustion, as a result.

The completeness of hydrogen combustion in oxygen is also strongly influenced by the rate of cooling of high temperature steam. It depends to the greatest extent on the type of heat carrier used (water or steam), as well as the method of its mixing with combustion products. Too high cooling rate leads to a "quenching effect" of the high temperature steam. A significant influence of this effect on the completeness of hydrogen combustion was noted in the work [12]. Its manifestation takes place in three stages. At the first stage a sharp cooling of the high temperature steam near the relatively cold walls of the combustion chamber is possible, however, due to the small amount of high temperature steam subjected to such cooling (about 5%) and the not very high rate of its cooling, the effect of this stage on the combustion efficiency is not great and is up to 0.006% for hydrogen and up to 0.04% for oxygen. An experimental study of this stage and its contribution to the completeness of combustion is very difficult to carry out, since all the experimental studies carried out were carried out with the addition of a coolant to the high temperature steam, the effect of which is much more significant as will be shown below.

At the second stage a cooling component is supplied, the mass flow rate of which is several times greater than the mass flow rate of high temperature steam. In this case, if the cooling component (steam or water) is supplied too quickly, especially directly into the combustion zone, a sharp decrease in the reaction rate occurs due to a decrease in the concentration of active components in this zone. As a result, some of the components and intermediate products of the combustion reaction do not have time to react.

At the third stage, the high temperature steam is abruptly cooled by a cooling component. In this case, due to the fact that at high temperatures the decomposition of water into its main components occurs, the combustion temperature in the combustion chamber is about 3600 K, the mole fractions of hydrogen and oxygen in such a steam are maximum. Therefore, the influence of the quenching effect on the completeness of hydrogen combustion can be very large. For example, let's take the data presented in the work [14] for steam at a pressure of 0.1 MPa (figure 1). Abrupt cooling of the high-temperature flow can lead to significant underburning of the fuel. The authors explain the reason for
the decrease in the completeness of combustion by the fact that a lower water temperature provides a faster heat removal from the combustion zone, which reduces the rate of the reaction.

Figure 1. Equilibrium distribution of molar fractions of components in steam at a pressure of 0.1 MPa.

It should be noted that the quenching effect in highly heated steam is used directly in the production of hydrogen by thermal decomposition of water, in which, on the contrary, sharp cooling and dilution of the flow are used to obtain the maximum amount of hydrogen. [14, 15]. Experimental studies carried out in [14] showed that the dependence of the molecular hydrogen content is almost linearly dependent on the cooling rate of the high temperature flow, and the minimum cooling rate should be more than 105 K/s. Thus, to prevent the formation of unburned hydrogen in a HCU, the cooling rate of combustion products should be significantly lower than 105 K/s. It is quite difficult to provide such a cooling rate when used as a water cooler. To do this, it is necessary to ensure its supply in several stages, while the water used to cool the combustion chamber must be preheated in it to a temperature close to the boiling point, in this case, when it is injected into the HCU, it will partially evaporate, which will reduce the rate of cooling of combustion products. A similar cooling scheme was used on all similar devices, as shown above.

A lower rate of cooling of the combustion products of hydrogen and oxygen can be achieved when using water vapor as a cooling component. Significant disadvantages of using water vapor are the lower cooling efficiency of the combustion chamber and the need for the steam itself of the required pressure. As a result, in such structures in the combustion chambers, there is practically no internal cooled insert, which prevents the ingress of cooling steam into the combustion zone. This leads to the fact that the completeness of combustion begins to be strongly influenced by the second stage of the quenching effect, which can significantly reduce the completeness of combustion of hydrogen. The option using an internal insert cooled by low-temperature steam can be applicable in the case of a very large amount of steam, for example, at nuclear power plants with wet steam turbines, but such designs have not yet been developed. Experimental data on the operation of installations with a similar cooling steam supply scheme are also lacking.

4. The main areas of application and thermodynamic features of the HCU

Being universal and compact devices, HCU allow implementing various thermodynamic cycles of energy conversion using modern and promising steam turbine technology. While using them, the
restrictions on the temperature of the superheated steam, determined by the materials of the boiler units and steam pipelines, are practically lifted and it is possible to modernize the existing power plants, which makes it possible to fully realize the power reserves of the existing equipment, increase the efficiency of power plants and reduce the specific heat consumption per kilowatt-hour of electricity generated.

Among the main areas of application of the HCU are the following:

- Additional storage superstructures for the production of peak capacities;
- Superheating of steam in front of the turbine;
- Hydrogen energy storage systems.

When using the HCU for turbine generators of turbines K-160-130, K-200-130, K-300-240 and a number of others, it was found that they have a margin of 10% at nominal and maximum power, i.e. modernization of the power plant in order to increase power by 10% by increasing the temperature of steam superheating from 540 °C to 565 °C and its consumption can be carried out with minimal costs by including in the HCU scheme as a superstructure to the turbine, and the turbine itself and the turbine generator can remain unchanged. In this case, the specific fuel consumption is reduced by 1.2...1.5 %. Calculated studies of the thermodynamic efficiency of steam turbine power plants of various types (new high temperature and modernized existing ones) with HCU show that the efficiency of using hydrogen for electricity generation in such plants can exceed 60% [10].

A side effect of using the HCU as a superstructure is the possibility of providing additional superheating steam before the steam turbine. The use of such schemes has recently been considered for nuclear power plants [7]. It should be noted that in the European part of Russia, where the share of nuclear power plants (23.2 million kW) and poorly maneuverable thermal power plants (58 million kW) is relatively large, today the required maneuverability of generating capacities is not provided (there is one Zagorsk pumped storage power plant (PSP) with a capacity 1200 MW).

An important potential area of HCU application is steam superheating before wet steam turbines, at geothermal power plants (GeoPP) [6]. The very name of wet steam turbines indicates that they operate on wet steam, and their efficiency (14...38%), as a rule, is significantly lower than that of turbines operating on superheated steam (up to 52%). At the same time, the use of wet steam turbine plants is most often due to the peculiarities of steam generating plants, for example, at a nuclear power plant, this is a restriction by the parameters of the reactor, and at a GeoPP, it is limited by the parameters in a geothermal well. A partial solution to this problem can be the use of additional superheating of steam to reduce its moisture content in the flow path of the turbine, as well as at the outlet from it. In this case, as a result of a decrease in steam moisture in the flow path of a steam turbine, its internal efficiency increases, which in general makes it possible to increase the overall (taking into account the cost of producing hydrogen) efficiency of the power plant by 3...4% when replacing a wet steam turbine with a turbine using superheated steam. In addition, reducing the moisture content of steam in the flow path of the turbine, and especially at the outlet from it, will avoid premature wear of the turbine blades, and, consequently, will reduce the cost of overhaul, increase reliability and reduce the number of forced shutdowns. It should be noted that the literature sources do not pay sufficient attention to the technical, economic and thermodynamic assessment of such schemes, which is primarily due to the lack of prototypes of hydrogen-oxygen steam superheating systems, which makes it difficult to assess their cost and technical characteristics.

HCU can also be used in hydrogen energy storage systems. One of the latest schemes using hybrid air-hydrogen energy storage is shown in [5]. A combined scheme of an air storage gas turbine power plant is proposed, in which the heat of combustion of hydrogen in oxygen obtained by electrolysis is used to heat the air in front of the turbine. Hydrogen as an energy accumulator has a number of advantages over other storage systems: high density of stored energy (up to 38 kWh/kg (t)), absence of harmful emissions during operation, widespread in nature. However, the main advantage is the very low cost of energy storage, which is about 15 $/kWh, which is unattainable for any other known storage system. The use of hydrogen makes it possible to solve the main problem of compressed air energy storage devices associated with large storage volumes and the use of additional organic fuel for
heating by creating a combined hydrogen-air gas turbine storage system. The product of hydrogen combustion in oxygen is high temperature steam, which allows it to be used for heating air from a storage facility by mixing, eliminating the formation of harmful substances, unlike, for example, burning hydrogen directly in air.

5. Conclusion
An analysis of the main features of hydrogen combustion units showed that they must be taken into account in order to create effective and safe structures, especially when used in the field of power engineering. In this case, it is especially important to take into account possible problems arising from the formation of explosive mixtures of hydrogen and oxygen. An especially strong influence on this can be exerted by the underburning of hydrogen, which occurs when the high-temperature steam is not cooled correctly and the mixing process is improperly organized.

Plants based on HCU, superheaters and air heaters, characterized by high power density, environmental friendliness and maneuverability, can be widely used in traditional, distributed and autonomous power generation in the power range from 100 kW to 100 MW. In general, the main critical problems for the successful creation of prototypes of such installations have now been resolved. It was possible to create a wide range of units of various capacities and different types of coolants, combining compactness, efficient cooling of the most heat intensive units and high efficiency of hydrogen combustion. Nevertheless, further additional research is required to improve their effectiveness and expand the field of application.

Due to the fact that the scale of the use of hydrogen technologies in the energy sector is small due to the relative high cost of such basic elements as electrolyzers and storage systems, the field of use of hydrogen-oxygen plants, implying the consumption of large amounts of hydrogen, is limited. It can be assumed that as these elements develop and become cheaper, hydrogen-oxygen plants will also receive additional development.

References
[1] Schastlivtsev A and Borzenko V 2017 Hydrogen-oxygen steam generator applications for increasing the efficiency, maneuverability and reliability of power production Journal of Physics: Conference Series 891(1) 012213
[2] Stathopoulos P, Sleem and C Oliver Paschereit 2017 Steam generation with stoichiometric combustion of H2/O2 as a way to simultaneously provide primary control reserve and energy storage Appl. Energy 205 692-702
[3] Aminov R, Schastlivtsev A and Bairamov A 2017 On the issue of investigating the kinetics of processes in dissociated water steam International Journal of Hydrogen Energy 42(32) 20843-20848
[4] Schastlivtsev A, Dunikov D and Borzenko V 2019 Experimental study of the processes in hydrogen-oxygen gas generator International Journal of Hydrogen Energy 44(18) 9450-9455
[5] Schastlivtsev A and Nazarova O 2016 Hydrogen–air energy storage gas-turbine system Thermal Engineering (English translation of Teploenergetika) 63(2) 107-113
[6] Dunikov D 2018 Cycle improvement and hydrogen steam superheating at Mutnovsky geothermal power plant Case Studies in Thermal Engineering 12 736-741
[7] Aminov R and Egorov A 2019 Hydrogen-oxygen steam generator for a closed hydrogen combustion cycle International Journal of Hydrogen Energy 44(21) 11161-11167
[8] Fröhliche K and Haidn O 1997 Spinning reserve system based on H2/O2 combustion Energy Conversion and Management 38(10) 983-993
[9] Malyshtenko S, et al. 2012 Effectiveness of steam generation in oxyhydrogen steam generators of the megawatt power class High Temperature 50(6) 765-773
[10] Gryaznov A, et al. 2008 Hydrogen steam generators for stationary energy applications 17th World Hydrogen Energy Conference, WHEC 2008 (2008) Brisbane, QLD
[11] Kato S and Nomura N 1997 *Hydrogen gas-turbine characteristics and hydrogen energy system schemes* Energy Conversion and Management 38(10) 1319-1326

[12] Haidn O, et al. 1998 *Improved combustion efficiency of a H2O2 steam generator for spinning reserve application* International Journal of Hydrogen Energy 23(6) 491-497

[13] Shternfeld H and Wolfmuller K 1986 *The hydrogen/oxygen spinning reserve system – an approach to the economic generation of electricity from hydrogen* VGB Kraftwerkstechnik 66 675-683

[14] Lédé J, Lapicque F and Villermaux J 1983 *Production of hydrogen by direct thermal decomposition of water* International Journal of Hydrogen Energy 8(9) 675-679

[15] Ihara S 1978 *Feasibility of hydrogen production by direct water splitting at high temperature* International Journal of Hydrogen Energy 3(3) 287-296