Experimental study of the processes in high-temperature hydrogen-oxygen air heater

A I Schastlivtsev, V I Borzenko

Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 bld. 2, Moscow, 125412 Russia

h2lab@mail.ru

Abstract. The results of experimental investigations of steam and steam-gas generation in high-temperature hydrogen-oxygen air heater with thermal capacity of 200 kW are presented. The influence of rapid mixing of air with the steam produced by hydrogen–oxygen combustion on the hydrogen completeness of combustion and the influence of cooled liner length on the NOx formation are studied. The fact is established that pressure increase in combustion chamber increases the hydrogen combustion completeness and practically has no influence on the nitrogen oxides formation.

1. Introduction

In the near future hydrogen can become one of the main mean for the storage of renewable energy sources (RES). Hydrogen utilization in fuel cells is characterized by high efficiency of energy transformation and the absence of emissions, but if increased capacity of power production, the schemes based on hydrogen combustion could become more feasible. The evident way of hydrogen utilization is admixing to fossil fuels, namely natural gas, with further combustion in gas-turbine combustion chamber. This, Power-to-gas technology is well-known [1, 2]. However, this way fits only the territories with developed gas transportation network and is not free from hazardous emissions, though decreases them to some extent.

Full replacement of fossil fuels by hydrogen is the way for the creation of emission-free and autonomous energy storage systems. At full transition to hydrogen fueled gas turbine plants the main problem is the change in operation conditions of combustion chamber of gas turbine causing NOx emission increase [3-7]. This problem is connected with the fact that modern combustion chambers using fossil fuels are designed not only to produce as little NOx as possible but also to decrease CO emission. While for the reduction of NOx emission the decrease of temperature down to 1600…1700 K is needed, the optimal for CO minimization temperature lies between 1800 and 1900 K. Thus, for the NOx emission decrease substantial modification or new design of combustion chamber are necessary. It is known that NOx emission grows exponentially with the flame temperature and linearly with the duration of combustion products presence in high-temperature zones, so the basic requirements for hydrogen combustion chambers are the decrease of maximal temperature and the combustion process localization at short distance of the flame tube with 5…6 ms presence of combustion products in high temperature zones, the targets being the main focus of modern research [4, 5, 8-12]. Also, the significant influence was discovered of combustion chamber pressure and oxidant excess factor [5, 13]. In [14] rapid combustion products cooling by adding big water amount was considered. It is shown that rapid
cooling is responsible for “quenching” effect which results in the increase of residual hydrogen amount after the combustion chamber.

The way for complete avoidance of hazardous emissions is hydrogen combustion in oxygen with steam being the only product of reaction. This becomes actual as electrolysis being one of the main sources of hydrogen obtained from renewable power and oxygen is byproduct of the process. This approach was studied in [15-17] with the focus on utilization of high temperature steam produced by hydrogen combustion in stationary steam turbines. This technology gives the way for hydrogen utilization with minimal investment in the equipment however for the modern steam turbines reaching capacities of 1000 MW big amount of hydrogen is needed. Long start-up period of steam turbines also prevents them from being used for energy storage systems.

The perspective basis for energy storage is hydrogen combustion in oxygen with further mixing of produced steam with air. The air heated up by this mixing to the certain temperature can be used in conventional gas turbine. One of the important peculiarities of this technology is full avoidance of NOx origination due to absence of nitrogen in the combustion area. This method could serve as the basis for the development of hybrid hydrogen compressed air energy storage system (H2-CAES) [18]. The principle of the operation of the H2-CAES is the following: during the peak-off hours the energy accumulation is conducted in two streams. The first stream is electrolysis which provides hydrogen and oxygen for further storage. The second stream is air compression. The air cooled after the compression is also stored.

In the power generation mode, the air from the storage first is fed into the regenerator for heating by the gas turbine exhaust gases up to 200…350 °C and after that to H2O2 - combustion chamber for heating up to 850…950 °C due to reaction heat of hydrogen combustion in oxygen. The design of H2O2 - combustion chamber provides the combustion of hydrogen in oxygen prior to mixing of the produced high-temperature steam with air which leads to air heating up to the required temperature.

Almost all publications on the NOx origination at hydrogen combustion focus on the case of hydrogen combustion in air. The authors have not found publications on interaction of air with high temperature hydrogen combustion products. In this connection experimental investigations were planned with the use of technology described in [17-19].

2. Experimental setup

For the experimental investigations of the processes in hydrogen-oxygen steam generator coupled with the system for steam-gas preparation for the further utilization in steam turbine, 200 kW thermal power device was developed and manufactured. The steam generator first provided hydrogen combustion in oxygen in combustion chamber and after that mixing of high temperature reaction products with air. The scheme of experimental high-temperature hydrogen-oxygen air heater of 200 kW(t) is presented in figure 1.

Mixing unit with spark is mixing and igniting the main flows of hydrogen and oxygen fed to combustion chamber. The supply of the gaseous components of fuel and oxidant is arranged in the following way. Gaseous oxygen is fed to spark unit where during the ignition its partial ionization and heating up by the spark discharge take place. After passing the spark unit hydrogen is fed to combustion chamber through the central hole of the nozzle. Gaseous hydrogen is fed through the pair of inlet fittings of the mixing unit to the main collector and after that through sixteen 0.5 mm nozzles to combustion chamber where due to its mixing with ionized oxygen the mixture ignites.

Combustion chamber is the most thermally loaded part of high-temperature hydrogen-oxygen air heater. As a special measure of combustion chamber wall thermal protection, air cooled liner is installed between the combustion zone and the outer wall. After passing the gap between the liner and the wall, heated-up air is fed to the combustion chamber. In order to avoid the NOx origination due to the presence of air in high-temperature area of the combustion chamber, the liner length should be optimized. Two lengths of 35 mm and 70 mm have been studied in this research.
Figure 1. The scheme of experimental high-temperature hydrogen-oxygen air heater of 200 kW(t): 1 – spark, 2 – mixing unit, 3 – H₂O₂ – combustion chamber, 4 – mixing chamber, 5 – outlet nozzles, 6, 7 – near wall temperature sensors, 8 – central flow temperature sensor; 9 – pressure sensor outlet, 10 – chemical probe outlet.

The mixing chamber is a thick-wall cylinder channel with 50 mm inner diameter and 150 mm long. The flow of air used for combustion chamber wall cooling is fully mixed here with high-temperature combustion products.

Temperature sensors were placed in 40…250 mm from the combustion zone which gave the data on combustion products temperature change during cooling and mixing with air.

3. The results and discussions

The first result of the preliminary study is the fact that rapid mixing of air with the combustion reaction products having temperature up to 3600 K leads to their strong dilution and the growth of residual hydrogen in the outlet flow (up to 1.5%). That was the reason for the use of cooled liners of various lengths in order to try to separate combustion and mixing areas along the combustion chamber. Such a supply scheme according to the preliminary calculations decreases the volumetric content of residual hydrogen down to 0.5…1.2 % [19] and the increase of the liner length prevents the NOx origination. The limit of the cooled liner length is imposed by the complications in its cooling. For the calculation of heat transfer coefficient from the combustion product side the correlation for turbulent flow around a plate [20] with correction connected with steam temperature up to 4000 K and dissociation [21] can be used:

\[ Nu = 0.0296 \cdot Re^{0.8} \cdot Pr^{0.43} \cdot (1.27 - 0.27 \cdot T_{w.g} \cdot T_g^{-1}) \]  

\( T_{w.g} \) – wall temperature from the combustion product side;  
\( T_g \) – combustion products temperature.

From the coolant side the correlation for stabilized flow of gaseous medium in rectangular channel can be used [20]:

\[ Nu = 0.023 \cdot Re^{0.8} \cdot Pr^{0.4} \cdot (T_{w.a} \cdot T_a^{-1})^{0.37} \]  

\( T_{w.a} \) – wall temperature from air side;  
\( T_a \) – air temperature.

The limit of the cooled liner length according to the calculations at given thermal capacity of the high-temperature hydrogen-oxygen air heater and gas outlet temperature in 1200 K is 94 mm. Experimental investigations showed the average NOx content in 38 mg/st.m³ for 30 mm long liner with the decrease down to 11 mg/st.m³ for 70 mm long. The estimated air flow fed for the cooling accounted for 119 g/s at thermal capacity of hydrogen-oxygen air heater of 110 kW. In figure 2 gas temperature...
inside the mixing chamber (pos. 7, 8 in figure 1) and temperature at the outlet of cooled part of combustion chamber (pos. 6 in figure 1) are presented for the case of tests with 70 mm cooled part of hydrogen-oxygen air heater.

Figure 2. Temperature in H2O2-combustion chamber.

The next stage of the experimental investigations included the study of the combustion chamber working pressure influence on the hydrogen combustion completeness and on NOx origination. Three tests were conducted at 0.6, 1.2 and 2.4 MPa and at the 70 mm long cooled liner. The experimental investigations showed that pressure increase in combustion chamber increases the hydrogen combustion completeness and practically has no influence on the nitrogen oxides formation. The results of experimental investigations are given in table 1.

Table 1. The results of experimental process investigations in hydrogen-oxygen gas generator at various pressures in combustion chamber.

| Combustion chamber working pressure, MPa | 0.6 | 1.2 | 2.4 |
|----------------------------------------|-----|-----|-----|
| Outlet gas average temperature, K      | 1121| 1145| 1164|
| NOx content, mg/st.m³                  | 11.2| 11.3| 11.5|
| Residual hydrogen content, % (vol.)    | 1.4 | 1.1 | 0.7 |

4. Conclusion
Experimental study of the processes in 200 kW(t) experimental high-temperature hydrogen-oxygen air heater was conducted. The temperature of the generated gas accounted for 954…1164 K. The double extension of the cooled liner length (from 35 to 70 mm) gave the decrease of nitrogen oxides content from 38 to 11 mg/st.m³, which was substantially lower than the requirements to even perspective combustion chambers of gas-turbine units. It has been also proved that rapid mixing of air with the products of the combustion complicates the full combustion of hydrogen and leads to high content of the residual hydrogen in the outlet gas (up to 1.5%) thus decreasing the efficiency and potential safety of the technology. The decrease of working pressure in the combustion chamber leads to the increase of
hydrogen combustion completeness down to 0.7% of residual hydrogen at 2.4 MPa and has no visible influence on NOx origination. For the proposed H2-CAES systems, which use air as the coolant for combustion chamber wall and steam-air mixture as actuating medium for the gas turbine, high pressure turbines are more preferable from the point of view of efficiency and safety.

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