Experimental investigations of the processes in gas generator of hydrogen-air energy storage

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Abstract. This paper describes the results of experimental investigation of the sample of the hydrogen-air gas generator unit with the expected average power of 65 kW. In total 5 test runs were made. Two tests showed that the mass flow and outlet gas temperature was in agreement with the designed parameters. Additional attention should be paid to the cooling system design for the combustion chamber. In future such a gas generator in couple with the suitable gas turbine unit could be a part of the renewable energy accumulation system e.g. of hydrogen-air energy storage.

1. Introduction

The power generation and accumulation systems demand high reliable, efficient and ecological energy conversion technologies as gas turbines are likely to play a significant part of the future power generation scenarios. The hydrogen may effectively accumulate the energy generated from the wind or solar power stations as well as biomass gasification. For this there is a necessity in constructing of hydrogen combustion chamber which allows the stable, reliable and safe combustion occurring with the low NO\textsubscript{x} emission level. Also according to [1] there is a large difference between the hydrogen physical properties and the carbon fuels. So the current essential task is the development of dry-low-NO\textsubscript{x} combustion (DLN). The experimental unit in here included 0.3 mm micromix combustion chamber and it showed its low NO\textsubscript{x} percentage over operation time. The test burner was scaled for the gas turbine of 335 kW electrical and pneumatic power. Gaseous hydrogen was injected through injectors perpendicularly to air flow by means of guiding panels for the air. The comparison of three combustion models showed the good agreement of these models to one another. But the Eddy Dissipation Concept which combined chemical kinetics and turbulent effects got the closest results to the experimental NO\textsubscript{x} emissions data.

In [2] the combustion dynamics was described of the lean-premixed hydrogen-air flames. The high purity hydrogen was used as a fuel. For the comparison the high purity methane fuel was used in this case. The combustion test rig consisted of 60 injector multinozzles. The combustion chamber was made of a fused quartz pipe which was cooled by the air. The varying combustor construction is a key feature of the experimental rig (1200-1800 mm). Cooling water system also was set up for the piston centered in the combustion chamber. The experiments showed that the hydrogen flames oscillated in this nozzle system in isolation and with only weak interactions. Finally obtained results let the authors describe the behavior of lean hydrogen-air flames and show the self-induced instabilities at a wide
range of conditions. All these results are also a part of the modern experimental investigations for development of hydrogen gas turbine systems.

The hydrogen combustion experiments are also vital for the nuclear power industry [3] as there hydrogen can be released in a reactor core melt accident. This described study was carried out using new Hydrogen Middle scale Test facility which can assess the efficiency of the hydrogen mitigation. The experimental setup consisted of a stainless steel tank with two domes connected at bottom and top positions. The paper concentrated on the combustion of the hydrogen-air mixture at three elevation level and also three concentration level (to 10% vol.). Four photodiode sensors in the axial direction could track the movement of the flame front. For the concentrations less than 10% the hydrogen was partially burned and this process was local. At 10% vol. H$_2$ concentration the hydrogen burned almost completely. All directions of flame propagation were a significant feature for this concentration. In [4] a thorough summary of the experiments and computational modes for hydrogen distribution and hydrogen combustion for containment hydraulics has been elaborated. What for the computer codes Lumped Parameter Codes and Computational Fluid Dynamics codes were described.

The results of experiments on the combustion regimes of lean and stoichiometric hydrogen-air mixture (up to 30 % H$_2$) are analyzed in [5] in a closed rectangular chamber. There were a smooth channel, a channel with metal grid filling a quarter of space and a channel completely filled with a metal grid. This was made for modeling a gap between an assembly of a fuel cell and a housing. Also five types of flame propagation regimes were systematized. But the main goal was to measure the hydrogen-air combustion behavior, flame acceleration and deflagration-to-detonation transition in a closed geometry.

Numerical studies were also devoted to the flame propagation of the lean 15% hydrogen-air mixture in the confined vessel of 4 cm diameter [6]. The results showed that mixing of water micro-droplets to the hydrogen-air could lead to the significant acceleration of the flame and the combustion. This effect was more significant for larger water droplets. The author also mentioned that the evaporation of relatively large water droplets can cool the combustion products which in turn can reduce NO$_x$ emissions. Another study [7] was devoted to the initiated ignition of the lean hydrogen-air mixtures at atmospheric pressure by high-speed colour cinematography alongside with the numerical simulation of the process.

In [8] the combustion scheme for hydrogen-oxygen mixture stoichiometric combustion in the counter-current flow of water steam was implemented along with the combustion chamber of a high-temperature steam superheat. The superheated steam temperature at the combustion chamber outlet reached 1350 K. Also the optimum modes for hydrogen-oxygen mixture outflow were determined for its steady combustion in the counter-current water steam flow core. The geometry of combustion chamber flow section allowed to regulate the relative flow of the steam superheat in a wide range. The resulted steam temperature at the combustion chamber outlet provides prospects for development of steam turbines and combined power plants.

The goal of present work is obtaining experimental parameters of gas-dynamic processes of hydrogen-air gas generator in a wide range of fuel, oxidizer and ballasting air consumption. Such a generator was designed for using in the cycle with the gas turbine unit of 50 kW capacity which in its turn could be a part of the hydrogen-air accumulation system for the renewable energy sources e.g. [9].

2. Experimental details

The experimental hydrogen-air gas generator unit (figure 1) for process research is made of stainless steel and consisted of a mixing unit, a combustion chamber, a simulator nozzle, a flange, and an air casing with an O-ring. The whole length of unit is 389 mm without the auxiliary equipment, the combustion chamber length is 259 mm with the larger inner diameter 81 mm. The experimental testing unit for hydrogen combustion with a capacity of up to 200 kW [10] of the Joint Institute for High Temperatures of the Russian Academy of Sciences was upgraded for this investigation.
As for the combustion chamber in these experiments the process of combustion (in figure 2) can be classified neither diffusion nor kinetic. A premixed part of hydrogen and oxygen is ignited in the central channel with the ignition spark first. After that the main part of hydrogen coming from the 16 circumferential orifices is being ignited due to the turbulent mixing. The necessary part of the experimental unit is the air casing for creating low-temperature wall layer and reducing the heat density of the edge. As it can be seen in figure 2 the air casing has a ribbed surface with a high heat transfer rate, the ability to resist mechanical stress and endurance to the high pressure. The air casing was designed for the mass flow 280 g/s in order to cool effectively the gas generator walls. Air goes through the gap between the casing and the wall and only afterwards enters the combustion chamber. The outlet gas temperature 690 °C was defined from the high-temperature strength condition for the gas turbine blades.

The used automation system made it possible to ensure the safety of the hydrogen-air gas generator operation and its emergency shutdown. The experimental unit was connected to the main pipelines for supplying hydrogen, oxygen and air from the corresponding gas tanks. The entire experimental unit was tested by high pressure beforehand. During the tests of the experimental unit two starts for tuning and two control starts were carried out with an expected power of 60 and 72 kW.
In the first test the optimal starting mode of the hydrogen-air gas generator was determined and the cyclogram was adjusted since the combustion broke for 10 s due to a sharp supply of oxygen.

Taking this into account, in the second test the supply of increased flow rates of hydrogen and oxygen was made earlier. But due to the failure of the air pressure reducing valve and a decrease in the consumption of cooling air the gas temperature at the outlet increased to 1394 °C which of cause exceeded for a significant value the designed outlet temperature.

The third control start was performed with an increased hydrogen flow rate and the outlet gas temperature reached 634 °C.

In the fourth also control start the hydrogen consumption was increased more and the outlet gas temperature reached 723 °C. During this test, outlet gas was also taken into a special tank for analysis for the content of nitrogen oxides (NO\textsubscript{x}). Analysis of this gas composition showed the content of nitrogen oxides in the concentration of 14.7 ppm which suited the expectable values.

In table 1 we summarize the main average experimental parameters for the tests.

|                              | 3\textsuperscript{rd} start | 4\textsuperscript{th} start |
|------------------------------|------------------------------|----------------------------|
| Hydrogen pressure, atm       | 18.3                         | 10.87                      |
| Oxygen pressure, atm         | 29.1                         | 28.63                      |
| Air pressure, atm            | 26.8                         | 29.22                      |
| Hydrogen mass flow, g/s      | 0.5                          | 0.6                        |
| Oxygen mass flow, g/s        | 4                            | 4.8                        |
| Outlet gas temperature, °C   | 634                          | 723                        |

For the fourth start which was successful the mass flows and the measured temperatures are shown in the following graphs in figure 3 and 4. During all tests a significant decrease in the temperature of the air pressure reducing valve was noted, which in its turn at the increase of cooling air consumption could lead to the freezing and problems in operation with the high-pressure air tanks.

After all the control runs had been carried out, an additional study was made to study the emergency operation mode of the hydrogen-air gas generator unit and determine the most heat-stressed areas of the combustion chamber. For this the cooling air consumption was reduced by 85%. As a result the outlet gas temperature exceeded 1500 °C and the internal cooled air casing was partially melted. After examining air casing it was obvious that the most heat-stressed zone is located at a distance of 7-9 cm from the fire bottom of the mixing unit. Consequently in order to increase the reliability of the combustion chamber in this area it is necessary to intensify cooling or to reduce heat load by increasing the diameter of the combustion chamber in this area.
Figure 3. Hydrogen and oxygen mass flows over time. __O₂ set point, __O₂ mass flow, __H₂ set point, __H₂ mass flow.

Figure 4. Temperatures changes over time. T1 – outlet gas temperature, T2 – mixing unit wall temperature, T3 – cooling air temperature.

3. Conclusion
First the modern works devoted to the hydrogen combustion were described briefly. It was mentioned that quite a lot of attention is paid nowadays to the lean hydrogen mixtures combustion and flame propagation analyses and hydrogen combustion in mesoscale. In the field of nuclear power engineering also several experimental and numerical investigations are described. For the main topic the results of series of experiments with the novel construction of mixing unit for the hydrogen-air gas generator of kilowatt level are presented in the second chapter. It was concluded that the construction of the cooling air casing should be improved to some extent but for the designed outlet gas temperature of 690 °C it worked without fails. Choosing the reducing pressure valve, one also should take into account the gas consumption flow rate for the combustion in order to avoid freezing. Analysis for the NOₓ concentration at the outlet gas showed also permissible value. So as most of the runs here were successful such gas generator unit could be a key element for development of the hydrogen-air energy storage system for the different renewable energy sources.

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