Development of an automated system for experimental investigation of thermal processes in a hydrogen-oxygen steam generator

I M Molotov¹, A I Schastlivtsev¹, L V Yamshchikova¹ and I A Molotova²

¹ Joint Institute of High Temperature, Russia, 125412 Moscow, Izhorskaya, 13, Bd. 2
² National Research University "MPEI", Russia, 111250 Moscow, Krasnokazarmennaya, 14

h2lab@mail.ru

Abstract. The paper presents the results of the development and creation of an automated system of scientific research (ASSR). It provides experimental studies of heat and mass transfer processes in a hydrogen-oxygen steam generator (HOSG). The most relevant fields of application of hydrogen-oxygen steam generators are considered. The paper discusses the most relevant areas of application of hydrogen-oxygen steam generators, scientific and technical barriers to the introduction of technology and the features of the construction of ASSR for experimental research. The schematic diagram of the primary measuring transducers and the control mechanisms of the experimental stand are described. The choice of the configuration of the automated control and measurement system is justified from the point of view of completeness and reliability of the obtained data.

1. Introduction

Common knowledge that hydrogen-oxygen steam generators (HOSG) can be widely used in the energy industry [1], associated with increased maneuverability and reliability of nuclear power plants (NPPs), alignment of energy consumption schedules in the daily and weekly intervals, etc. [2], since they have high thermodynamic parameters of the generated steam, compactness, environmental friendliness, and fast start-up [3]. The joint use of a steam generator as part of a hydrogen storage complex integrated with a nuclear power plant can be the most effective [4, 5]. The main idea of this technology is that during the hours of minimum load, hydrogen and oxygen are produced by electrolysis of water, sent to storage, and during the hours of maximum load are used to generate energy by burning hydrogen in oxygen in a HOSG, increasing the power of the steam turbine, including for power supply to the NPP’s own needs in case of emergencies [6].

In previously published works, the efficiency of experimental samples of HOSG was shown and experimental data were obtained, which showed high dynamic characteristics and other technical parameters of promising HOSG [7]. However, for the introduction of HOSG in the energy sector, it is necessary to solve a number of important scientific and technical problems, namely:

- achieving more complete combustion of hydrogen in an oxygen environment [8, 9];
- providing more reliable thermal protection of the most heat-stressed sections of the combustion chamber of a HOSG;
studies of the hardening effect.

The design features of the new steam generator model are considered in [11]. The principal difference between the new sample is that the steam is cooled through the wall along the entire length, and the cooling zone has an increased length, compared to the previous samples of HOSG [8], sufficient to ensure a uniform decrease in the temperature of the combustion products, thus minimizing the tempering effect.

Common knowledge that the tempering effect [12] consists in a sharp decrease in the rate of chemical reactions during rapid cooling. Therefore, hydrogen, which is in a dissociated state at high temperatures, does not have time to recombine and form steam as a result of rapid cooling. Thus, during the operation of the installation, hydrogen gas can accumulate, which creates risks of an explosion and fire situation.

In this regard, the automated system for the study of processes on a new sample of the HOSG has the following features:

- input module with a channel polling rate of at least 200 ms for temperature and pressure measurement;
- digital input module with an input sampling frequency of at least 150 kHz for receiving data from turbine flow meters;
- a software package for dispatching control and data acquisition (SCADA), designed for operator control of experiments;
- remote secure installation management.

2. Experimental setup

A schematic diagram of the HOSG stand, including diagnostic and control elements, is shown in figure 1.

![Figure 1. Schematic diagram of the diagnostic and control elements of the test stand. Symbols on the diagram: HPR1...HPR4 – high pressure reducer, EV1...EV9 – electrovalve, FC1, FC2 – gas flow controllers, PS1...PS8 – pressure sensors, TS1...TS10 – temperature sensors, FM1...FM5 – liquid flow meters.](image)

The establishment of the studied mode of operation of the steam generator follows the general sequence of procedures. First, the gases-hydrogen and oxygen from cylinders with a pressure of up to 15 MPa are fed into the system of the experimental stand. The spark plug is triggered. Next, the hydrogen ignites and the flame spreads in the combustion zone. At the same time, the water flow is
supplied to cool the combustion chamber. The stationary mode is established by means of gas flow regulators. All elements of the steam generator housing have independent separate cooling from the common cold water collector, which is pumped through the cooling circuit and then drained into the hot water collector (figure 1). When the nominal operating mode is reached, the generated steam is sampled. After sampling, a stop is made by closing the electric valves that supply gas to the steam generator. Next, all gas channels are purged with nitrogen.

If the effect of quenching is minimized during vaporization in the experiment, then when sampling, according to the measurement method, in order to fix the volume of active particles in the resulting steam, it is necessary that the quenching process proceeds as efficiently as possible.

The sampling method is proposed and described in detail in [6, 8, 12]. Before sampling, argon is purged through the channels of the sampling system (figure 2). Then, after the pressure disturbances have calmed down, sampling begins. In this case, the extracted steam is diluted with argon and enters the capacitor (Pos. 5 figure 2). The remaining non-condensed components (hydrogen and oxygen in the argon atmosphere) are fed into the control sampling tank (Pos. 7 figure 2), which is pre-evacuated. Then the control sample is subjected to chromatographic analysis.

![Sampling scheme](image)

**Figure 2.** Sampling scheme. Symbols on the scheme: 1 – steam generator, 2 – steam selection, 3 – argon tank, 4 – purge line, 5 – cooler, 6 – condensate tank, 7 – sampler with pressure gauge, 8 – vacuum pump, 9 – chromatograph, 10 – personal computer, 11 – cold water, 12 – hot water.

All procedures (start-up, exit to the nominal mode, sampling, stop) are carried out according to the specified cyclogram of the experiment. A variant of the cyclogram for one of the modes is shown in figure 3. As can be seen from the example of the cyclogram, the time from start to stop is 35 seconds with a quick change of states of the control mechanisms of the stand. Therefore, the development of rapidly changing operations on the cyclogram was implemented using the created automated control system.
3. Automation and control infrastructure

The development strategy of the automated system was based on the following principles:

- a use of hardware components analog-to-digital input-output converters, which will be redundant in their characteristics in terms of accuracy and frequency of both measurements and discrete control. This may allow us to find out the permissible uncertainty of the measured parameters for the characteristic time of the process and, in the future, create prerequisites for the general industrial performance of a HOSG automation in the hardware, which has higher performance indicators and is available at a reasonable price

- the use of software tools, in which the above-mentioned infrastructure will allow you to study any selected mode of operation of the steam generator, by having the ability to implement a variety of flexible control algorithms, which, among other things, can be based on the processing and analysis of the measured parameters of the experiment in real time

In accordance with the chosen strategy, the LabVIEW graphical engineering software environment with National Instruments hardware was used to complete the task. A flowchart based on the selected hardware is shown in Figure 4.

Figure 3. Example of an experiment's cyclogram.

Figure 4. Structural diagram: 1 – electronic board PCIe-8361; 2 – cable MXI-Express; 3 – NI PXI-1078; 4 – analog I / O module NI PXI-6289; 5 - pressure sensors, thermocouples, turbine-type liquid flowmeters; 6 – relay module NI PXI-2568; 7 - gas electric valves, liquid electric valves, car spark plug, gas flow regulators Bronkhorst; 8 – cable RS232; 9 - display, control and power system E-8000; 10 – cable Ethernet; 11, 12 – push-button post relay and electric valve.
To implement the cyclograms of experiments, a variant of one of them is shown in figure 5, a classical finite state machine was used, which allows:

- perform automaton steps (different states of control mechanisms) in non-overlapping time periods
- synchronize the switching of control mechanisms (electric valve, spark plug, gas flow regulators) between the steps of a state machine

![Implementation of the start cycle diagram on the GUI.](image)

**Figure 5.** Implementation of the start cycle diagram on the GUI.

![Simplified algorithm of the program.](image)

**Figure 6.** Simplified algorithm of the program.

**Designations:**
1 – input of the experiment cyclogram, input of the number of steps of the state machine N
2 – a condition under which the green light on the remote button post is lit
3 – step number of the trigger state machine
4 – execution of the i-th step of the automatic start-up state machine
5 – moving to the sequence number of the next step of the state machine
6 – a condition in which the red button on the remote push button post is pressed or the steps of the machine start state of the installation have ended
7 – state machine stop
To enter a cyclogram, a table with explicit transitions is set on the graphical user interface (GUI) (figure 5). When the state machine is turned on, the column states are executed sequentially from left to right, changing the position of the control mechanisms in accordance with the assigned duration of the individual state.

When the program is executed, seven cycles are executed in parallel, which exchange data streams with each other using queues. The data display cycle on the GUI and the data logging cycle are continuously performed at a high frequency and, accordingly, display and record the states of the controls and the readings of the diagnostic elements. A simplified view of the program's algorithm is shown in figure 6.

4. Results and discussion

Figure 7 and table 1 show comparative tests for stoichiometric combustion at two different hydrogen flow rates and at an excess of oxygen. In all experiments, a stable mode of operation of the HOSG is observed. With the same flow rate of hydrogen at stoichiometry, the curve goes higher, because the excess oxygen slightly lowers the temperature of the steam. In PXI systems, the input modules provide data sequentially, so the frequency of polling the input channels for temperature, pressure, and cooling water flow was lower than expected. This did not affect the validity of the automated process control system created for the study of the completeness of hydrogen combustion at this stand, more detailed results of which are given in [7, 8]. The accuracy of the measurement method is described in [6].

![Figure 7](image)

**Figure 7.** Temperature in the core of a generated steam at the outlet, $\alpha$ – stoichiometry coefficient, C(H2) concentration of a remaining hydrogen gas.

**Table 1.** Comparative tests of HOSG operating modes.

| Average core temperature at the outlet, °C | Oxidizer excess ratio | Average pressure, atm | Approximate power, kW | The hydrogen content of the generated steam, vol.% |
|------------------------------------------|-----------------------|-----------------------|-----------------------|--------------------------------------------------|
|                                          |                       |                       |                       | Combustion zone | At the outlet of the cooling zone III |
| 945                                      | 1.0                   | 7.56                  | 100                   | 5.70              | 0.09                             |
| 778                                      | 1.0                   | 4.98                  | 80                    | 5.00              | 0.08                             |
| 749                                      | 1.4                   | 2.99                  | 80                    | 3.50              | 0.04                             |

5. Conclusion

In this work, the technological development of the automated control system of thermal processes for a new sample of the HOSG is performed. The developed automated process control system in terms of software and hardware was installed and implemented on an experimental stand, on which a new sample of the HOSG was installed.
The software and logic control of the created automated process control system allows you to flexibly implement and test any control algorithms for promising HOSG that will be integrated into various power plant operation schemes. It is obvious that for general industrial applications, the created control and measurement system is redundant in its component base. However, it showed a high efficiency of obtaining experimental data due to the capabilities of the software package used, namely, the presence of SCADA and a flexible graphical programming environment.

During the study of the completeness of hydrogen combustion in an oxygen atmosphere at the stoichiometric ratio, for the first time the underburning of hydrogen at the exit from the HOSG lies in the range of 0.04 – 0.09 vol.%, which is an order of magnitude lower than at the previous stage of the study (0.26 – 1.21 vol.%) [8]. But the experimental values of the unreacted hydrogen content turned out to be slightly higher than the calculated values, which were estimated to be up to 0.006% of unreacted hydrogen [6]. Hence, we can conclude that it is possible to further improve the design of the steam generator.

The considered automated process control system under experimental conditions shows the reproducibility of the operating modes of the HOSG, the required efficiency of obtaining experimental data and increased safety during experimental work.

References
[1] Schastlivtsev A I and et al 2020 High Temperature vol 58 № 5 pp 733-743
[2] Schastlivtsev A I and Borzenko V I 2017 Journal of Physics: Conf. Series vol 891 № 1 p 012213
[3] Malysheenko S P and et al 2012 High Temperature vol 50 № 6 pp 765-773
[4] Aminov R Z and et al 2020 Int. journal of hydrogen energy vol 45 № 29 pp 14614-14624
[5] Malysheenko S and Schastlivtsev A 2015 High Temperature vol 53 № 4
[6] Aminov R Z and et al 2018 Combining nuclear power plants with multifunctional power plants (Moscow: Nauka) chapter 2 pp 60–62
[7] Schastlivtsev A I and et al 2019 Journal of Physics: Conf. Series vol 1370 № 1 p 012010
[8] Borzenko V I and Schastlivtsev A I 2018 High Temperature vol 56 № 6 pp 927-932
[9] Schastlivtsev A I and et al 2020 Journal of Physics: Conf. Series vol 1652 № 1 p 012040
[10] Shapiro V I and et al 2011 Thermal engineering vol 58 № 9 pp 741-747
[11] Aminov R Z and et al 2020 High Temperature vol 58 № 3 pp 410-416
[12] Lédé J and et al 1983 Production of Hydrogen by Direct Thermal Decomposition of Water (Int. J. Hydrogen Energy) vol 8 № 9. p 675