Evaluation of the efficiency of combining wet-steam NPPs with a closed hydrogen cycle

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Abstract. Combustion of hydrogen in oxygen allows to produce high-temperature steam, which can be used to generate electricity in cycles of thermal power plants. Depending on combustion conditions the temperature of the generated steam can reach 3500-3600 K under the pressure of 6 MPa. The existing technical solutions imply direct injection of the cooling water or steam into combustion products to reduce the temperature and feed the resulting mixture into the steam cycle. The system of safe hydrogen steam superheating in the NPP cycle using the closed system of hydrogen combustion in the oxygen medium is considered in terms of efficiency of generating peak power at the main steam-turbine unit. This system allows to exclude hydrogen from entering the main NPP steam-power cycle, while unreacted oxygen circulates in the closed combustion system. The thermodynamic efficiency of the considered schemes of hydrogen steam superheating/overheating in the NPP cycle is determined.

1. Introduction
Combustion of hydrogen in oxygen allows to produce high-temperature steam, which can be used to generate electricity in cycles of thermal power plants. For example, at nuclear power plants utilization of the hydrogen production system allows for increasing the power and efficiency in the regular mode due to steam-hydrogen overheating of the main working fluid in the main steam turbine unit (MSTU) [1]. Under emergency situations related with blackouts, the hydrogen-oxygen steam generator can serve as a source of steam for power generation necessary to maintain emergency systems of the core cooldown [2].

Depending on combustion conditions the temperature of the generated steam can reach 3500-3600 K under the pressure of 6 MPa. The existing technical solutions imply direct injection of the cooling water or steam into combustion products to reduce the temperature and feed the resulting mixture into the steam cycle [3-4]. This approach has a significant drawback related with the effect of "quenching" upon injection of water or water vapor [5-6], which leads to decreased recombination efficiency while cooling combustion products and increased proportion of non-condensable gases.

Figure 1 shows the proposed schemes for power increase at the two-loop NPP, which are patented by the authors [7]. This scheme ensures safe and efficient combustion of hydrogen in oxygen by means of the closed combustion system. After the vapor condensing, the residues of the mixture of oxidizer and unburned hydrogen return into the hydrogen-oxygen steam generator. An increase in efficiency and capacity of nuclear power plants is achieved not only by increasing the steam temperature steam in the cycle of the steam turbine unit, but also by displacement of steam flow in the
regenerative heat system (RHS) or by increasing the flow of fresh steam in the main steam generator (MSG) by raising the feed water temperature above its nominal value. In this case, the cooling of combustion products is conducted through the heat exchange surface without mixing the working fluids.

![Diagram](a)  
(b)

**Figure 1.** Versions of hydrogen overheating of steam at the NPP:
- a – Displacement of steam flow to high-pressure heaters (HPH); b – Additional heating of feed water before the steam generator;
- 1 – hydrogen reheater; 2 – combustion chamber; 3 – cooling path for combustion products;
- 4 – condensate storage system with non-condensing gas extraction from combustion products;
- 5 – compressor; 6 – HPH; 7 – feed pump; I and II – cooling water from the low-pressure regenerative heating system.

Therefore, an essential advantage of the given scheme is the following:

- There is a possibility for burning hydrogen with the oxidizer excess ratio higher than 1. In this case, the unreacted oxygen is recovered in the combustion chamber for the combustion process and constantly circulates in the circuit.
- An increase in excess oxidizer ratio basically makes it possible to reduce the combustible losses to zero. This reduces the temperature of the combustion products, which increases the service life of the combustion chamber.
- Recirculation of combustion products (except for water vapor) in the combustion chamber allows avoiding the entry of hydrogen and oxygen explosive mixture into the working fluid of thermal power units.
- Kinetics of cooling combustion products without mixing with the fluid coolant to the temperature lower than at the start of the dissociation process makes it possible to use the heat from recombination of combustion products in the cooling process.

As a result of steam hydrogen overheating, the efficiency of the power unit increases by boosting the MSTU capacity by raising the initial steam temperature and by displacement of steam flow to HPH (Figure 1a). At this, we take into account an increase in efficiency of MSTU compartments which occurs due to the increase of steam temperature. According to the second scheme (Figure 1b), the feed water is preheated before the MSG above its nominal value. Thus, under fixed thermal capacity of the reactor the amount of steam generated in the MSG increases.

The necessity for additional cooling of combustion products by the main condensate occurs when the pressure of combustion products becomes lower than the pressure of the superheated steam, since the condensation temperature of water vapor in the combustion products lowers compared to the initial temperature of the heated vapor. In this case, at the pressure of combustion products higher than 6 MPa, additional cooling of combustion products is not required.
As mentioned above, the cooling water from the main NPP steam-power cycle can be used as the cooling flow in the given hydrogen-oxygen steam generator. According to [8], at the thermal capacity of the hydrogen-oxygen steam generator at 6 mW, the heating of the cooling water is 29.1 K, which corresponds to 608.5 kW of the heat output. The maximum temperature of the wall of combustion chamber remains within acceptable limits. The temperature of combustion products at the inlet to the cooling path is in the range of 3200-3500 K. Therefore they need further cooling to the temperature acceptable for usage in the high-temperature steam superheater (item 1 in Figure 1). In this case, the increase of pressure stimulates a slight increase of steam temperature due to reduction of water vapor dissociation coefficient according to the law of chemical equilibrium in line with the Le Chatelier principle.

2. Thermodynamic analysis

As follows from Figure 1, the cooled combustion products are delivered into the high-temperature steam superheater. Practically, this element is performed similarly to steam superheaters of conventional energy steam boilers, while the coolant (combustion products with oxygen) passes through the heat exchanger tubes. This is due to a small volume of the heating fluid and the need for overheating of a large volume of working fluid of the NPP steam-power cycle. Figure 2 shows an example of the general view of the given steam superheater.

To estimate the required area of the heat exchange surface of the steam superheater, we determine the coefficient of heat transfer from the heating to heated medium. The resulting heat transfer coefficient will also depend on the thermophysical properties of the metal of superheater tubes. Based on the established method for calculating heat transfer processes [9], Table 1 shows the results of calculating the required heat exchange surface, and the heat transfer coefficient for various heating medium pressures. For calculation purposes, the material is XH60BT, and the diameter of the tubes is 30 mm.

![Figure 2. The general view of the high temperature steam superheater: a – location of the superheater; b – front view of the superheater; c – all-welded part of the superheater; 1 – input collector; 2 – output collector; 3, 5 – piping of the upper and lower levels; 4 – superheater tubes; I – input of combustion products; II – output of combustion products; III – input of the heated steam.](image-url)
Table 1. Calculation results of the required heat exchange surface of hydrogen-oxygen steam superheater.

| Pressure in the combustion chamber, MPa | Heat transfer coefficient, W/m²·K | Cooled area, m² |
|----------------------------------------|-----------------------------------|----------------|
| 0.1                                    | 137.2                             | 2287           |
| 1                                      | 526.4                             | 602            |
| 6                                      | 1170                              | 291            |
| 8                                      | 1371                              | 259            |
| 10                                     | 1395                              | 252            |

As is seen in Table 1, the pressure buildup leads to an increase in the heat transfer coefficient due to significant rise in the heat transfer coefficient from the heating medium. At the same time, the required heat exchange area is reduced. In this case, reducing the pressure of combustion products to 0.1 MPa will lead to a significant increase in the required area of heat exchange surfaces. Thus, based on calculations of thermal engineering parameters of the proposed system of hydrogen overheating, we can conclude that the pressure buildup in the combustion chamber not only leads to upgrading the efficiency of hydrogen combustion in the oxygen medium, but also improves the efficiency of heat exchange in the steam superheating process.

It should be noted that realization of both versions of the closed system of hydrogen steam superheating will lead to increased steam flow into the MSTU condenser. It has been established that within a wide load range in the turbine, the flow of circulating water remains constant. In this case, we can assume that the heat transfer coefficient and specific heat in the condenser remains unchanged. In this case:

$$\frac{D_c}{D_{cn}} = \frac{t_s - t_{sc}}{t_{sn} - t_{scn}}$$

(1)

where $t_s$ and $t_{sn}$ are saturation temperatures within a condenser in the current and regular modes, respectively, $t_{sc}$ and $t_{scn}$ are the temperatures of the circulating water at the condenser inlet at the current and regular modes, respectively, $D_c$ and $D_{cn}$ indicate steam flow to the condenser under the current and regular modes, respectively.

It follows from the formula (1) that, while maintaining the temperature of circulating water at the condenser input under constant level, the saturation temperature of vapor in the condenser varies in proportion to the steam flow $D_c$ into the condenser, and with an increase of $D_c$ the vacuum in the condenser degenerates. In Table 2 for wet-steam turbine units, we provide the data relating capacity changes in the turbine units at the changes of pressure in the condenser by ± 1 kPa (0.01 kgf/cm²), within the limits of rectilinear sections in the correction curves, for the pressure in the condenser, as well as the changes in specific heat consumption under the regular load in the turbine unit [10]:

Table 2. Capacity changes in the turbine unit at the changes of pressure in the condenser by ± 1 kPa (0.01 kgf/cm²).

| Turbine | Power change, kW (±) | Change in specific heat consumption, % (±) |
|---------|----------------------|--------------------------------------------|
| K-220-44 JSC «Turboatom» (3000 rpm) | 3980 | 1.81 |
| K-500-65/3000 JSC «Turboatom» | 7960 | 1.59 |
| K-750-65/3000 JSC «Turboatom» | 8900 | 1.19 |
| K-600-60/1500 JSC «Turboatom» | 4250 | 0.85 |
| K-1000-60/1500-1 JSC «Turboatom» | 10350 | 1.04 |
| K-1000-60/1500-3 JSC «Turboatom» | 8300 (factory data) | 0.83 |
Considering the data presented in Table 2, calculations relating the thermal scheme of the K-1000-60/1500-1 steam-turbine unit allowed defining the capacity gains through realization of the proposed schemes of hydrogen steam overheating shown in Figure 1. The calculation results are shown in Figure 3:

![Figure 3](image)

**Figure 3.** Power increase at the MSTU depending on hydrogen consumption: 1, 2 and 3 – when realizing the scheme 1b for the pressures 8, 1 and 0.1 MPa; 4, 5 and 6 – when realizing the scheme for the pressures 8, 1 and 0.1 MPa

As is seen in Figure 3, an increase in steam consumption during realization of the scheme 1b gives the biggest power increase at the MSTU, which is explained by a more efficient heat supply with hydrogen fuel in terms of thermodynamics. Additionally, a decrease in the pressure of combustion products leads to a decrease in the power increase by an average of 12.4 MW and 2.94 MW for the scheme in Figure 1b and 1a, respectively.

For the comparative analysis of efficiency of the proposed hydrogen steam overheating system, we estimated the key indicators under various circuit solutions to application of the given system based on the method described in [11-13]. We introduce the efficiency indicator for using additional heat supplied through burning hydrogen fuel:

\[
\eta = \frac{N_{\text{add}}}{Q_{\text{add}}}
\]

where \(N_{\text{add}}\) is power increase, MW; \(Q_{\text{add}}\) is additionally supplied thermal power, MW. As a result of calculations, we determined the following final indicators at the pressure of combustion products of 0.1-6 MPa (see Table 3). As can be seen in Table 3, at the similar hydrogen fuel consumption, the scheme in Figure 1b is more effective. In this case, the enthalpy of fresh steam for the scheme in Figure 1b is slightly as a result of upgrading the flow rate of the fresh steam directed to the steam-hydrogen overheating. Moreover, in this case, the mass steam flow to the separator-superheater of the MSTU increases too.
Table 3. The results of comparing efficiency estimates of the NPP hydrogen steam over heating system (Figure 1a and 1b).

|                         | According to the scheme |
|-------------------------|-------------------------|
|                         | Figure 1a | Figure 1b |
| Pressure of combustion products, MPa | 6 | 1 | 0.1 |
| Hydrogen consumption, kg/s   | 7.9 |
| Increase in the flow rate of fresh steam, kg/s | 0 |
| Increase of steam consumption in the condenser, kg/s | 205 | 252 | 251 |
| Steam enthalpy, kJ/kg       | 2951 | 2877 | 2876 |
| Peak power, MW              | 250 | 223 | 218 |
| \( \eta \), %               | 25.32 | 23.52 | 22.94 |

As an alternative, we considered realization of the closed hydrogen combustion system based on Figure 1a and 1b without using the steam super heater. This approach allows for excluding a significant amount of the heat exchange surface of the steam super heater, which makes the whole system more compact. Thus, the power buildup at the plant is due either to the increase in the feed water temperature above the nominal rate, or due to exclusion of steam flow to the HPH of the MSTU, as well as by heating the main condenser within the condensation process and cooling combustion products. Table 4 presents the results of comparative analysis relating efficiency of the alternative version under the pressure of combustion products at 0.1-6 MPa:

Table 4. The results of comparative assessment of effectiveness of the closed hydrogen combustion system at nuclear power plants (Figure 1a and 1b) without the fresh steam overheating.

|                         | According to the scheme |
|-------------------------|-------------------------|
|                         | Figure 1a | Figure 1b |
| Pressure of combustion products, MPa | 6 | 1 | 0.1 |
| Hydrogen consumption, kg/s   | 5.68 | 5.68 | 5.7 |
| Increase in the flow rate of fresh steam, kg/s | 0 |
| Increase of steam consumption in the condenser, kg/s | 196 | 195 | 195 |
| Steam enthalpy, kJ/kg       | 141 | 140 | 134 |
| Peak power, MW              | 20.53 | 20.51 | 19.59 |
| \( \eta \), %               | 20.51 | 20.51 | 19.59 |

As shown in Tables 3 and 4, realization of the closed hydrogen burning system at NPPs without fresh steam overheating is least effective in terms of using heat from hydrogen fuel. In this case, preheating the water supply above the nominal rate is more effective in terms of thermodynamics, since among the considered versions, the average heat flow temperature is at the highest level. By analogy with hydrogen steam superheating (Figure 1a and 1b), the pressure buildup of the combustion products leads to increasing utilization efficiency of hydrogen fuel.

3. Conclusions
The system of safe hydrogen steam superheating in the NPP cycle using the closed system of hydrogen combustion in the oxygen medium is considered in terms of efficiency of generating peak power at the main steam-turbine unit. This system allows to exclude hydrogen from entering the main NPP steam-power cycle, while unreacted oxygen circulates in the closed combustion system.
As a result of calculation of heat and mass exchange processes, we determined the required parameters of the heat exchange surfaces to provide operation of the main elements of the proposed system under the given overheating level to ensure pressure in the combustion chamber of hydrogen-oxygen steam heater from 0.1 MPa to 10 MPa. As calculations showed, an increase in the pressure of the combustion chamber leads to increasing efficiency of hydrogen combustion and decreasing the required heat exchange surface of the cooling path for combustion products.

The thermodynamic efficiency of the considered schemes of hydrogen steam superheating in the NPP cycle is determined. Thus, for the power units based on VVER-1000, the increase in electric power was 218-250 MW under removal of steam flow to the high pressure heater and 247-289 MW at increasing the feed water temperature after HPH. Therein, the efficiency of utilization of hydrogen fuel was 22.94-25.32% and 26.09 - 30.53%, respectively.

Thermodynamic efficiency of the closed hydrogen burning system without steam overheating is determined. This approach will allow to exclude the metal-consuming steam superheater, that will result in lowering the heat efficiency of hydrogen fuel, i.e. 19.59-20.53% at removal of steam flow by HPH and 19.66-21.68 under increasing the temperature of feed water after HPH.

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