Development of a multi-generating complex with combined fuel in the production of hydrogen and oxygen

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Abstract. The article presents the research result on increasing the energy efficiency of thermal power plants (TPP). The centralized production of hydrogen at thermal power plants by multigeneration is proposed. A multigeneration complex was developed with additional production of hydrogen and oxygen. An exergy and economic analysis was carried out for TPPs with an electrical capacity of 230 MW and a thermal capacity of 394 Gcal/h. The comparison of the TPP in the current mode and in the multigeneration mode at its transfer to the nominal mode with the aim of additional production of hydrogen and oxygen was performed. The efficiency of the plant transition to the multi-generation mode with both economic analysis and exergy analysis has been proved.

1. Introduction to multigeneration

Increase in power efficiency of thermal power plants is possible at multigeneration [1]. Multigeneration is the combined simultaneous production of at least two energy carriers and other useful products from a single primary energy carrier at the object of generation.

One of the most efficient energy sources produced at TPPs is hydrogen. The prospective use of hydrogen may contribute to an increase in the efficiency of the station [2-4]. Simultaneous production and consumption of hydrogen at TPPs can be characterized as a promising centralized production [5].

One of the most limiting factors of hydrogen application at thermal power plants is its high cost. In [6] methane is proposed as an alternative to hydrogen, but the use of methane requires expensive CO₂ capture systems. Therefore, the proposed work considers ways to reduce the cost of hydrogen directly at the TPP. Hydrogen production at thermal power plants was previously proposed in [7,8] while using steam conversion of natural gas with its further application in a high-temperature superheater to increase the steam parameters before the turbine.

Works [9-11] considered multigeneration complexes, producing electricity, thermal energy and CO₂. These complexes have 59% efficiency for gas fuel and 51% for solid fuel; they are environmentally friendly and are being put into operation today.

2. Scheme of a multigeneration complex

In this work, a multigeneration complex is developed. It is proposed to organize the production of hydrogen by various types of natural gas conversion (steam, carbon dioxide and oxygen) and electrolysis, both to increase the efficiency of TPPs and for external use. In order to increase the efficiency of hydrogen production, it is proposed to use heat from production and heating extraction...
during regenerative cooling of synthesis gas. The scheme of the proposed multigeneration complex is shown in figure 1.

Figure 1. Scheme of a multigeneration complex with additional production of hydrogen and oxygen. 1 – steam boiler; 2 – high-temperature boiler superheater; 3,4 – pipelines of supply of hydrogen and oxygen; 5 – system for hydrogen production by natural gas conversion methods; 6 – oxygen plant; 7 – heat exchanger for hydrogen heating; 8 – heat exchanger for oxygen heating; 9,10 – exhaust gases from the steam boiler; 11 – steam turbine; 12 – electric generator; 13 – condenser; 14 – heat recovery boiler; 15 – steam to the high-temperature boiler superheater; 16 – steam mixer; 17 – production extraction; 18,19 – lower and top heating extraction; 20 – steam from the steam boiler; 21 – electrolysis plant; 22,23 – synthesis gas supply and return pipeline; 24 – flue gas to carbon dioxide and oxygen plant; 25 – carbon dioxide and oxygen production; 26 – fuel to steam boiler; 27 – oxidizer to steam boiler; 28 – water to steam boiler; 29 – high parameters of steam turbine; 30 – axle turbine; 31 – electricity to consumer; 32 – electricity to electrolysis plant; 33 – water to electrolysis plant; 34 – electricity to oxygen plant; 35 – air to oxygen plant; 36 – oxygen to pipelines; 37 – oxygen to consumer; 38 – hydrogen in steam boiler; 39,40 – exhaust gases to the atmosphere; 41 – steam from steam turbine; 42 – water from condenser; 43 – make-up water; 44 – water treatment plant; 45 – pump; 46,47 – district heater; 48 – production steam to consume; 49 – steam to steam mixer; 50 – fuel to hydrogen production system by natural gas conversion methods; 51 – hydrogen to consume; 52 – hydrogen to pipeline; 53 – steam to hydrogen production system by natural gas conversion methods; 54,55 – oxygen to hydrogen production system by natural gas conversion methods; 56 – carbon dioxide to hydrogen production system by natural gas conversion methods; 57 – secondary products to heat recovery boiler; 58 – steam to steam turbine; 59 – water to heat recovery boiler; 60,61 – exhaust gases to the atmosphere.

3. Assessment of the proposed system effectiveness
To assess the effectiveness of this system, the exergic efficiency was calculated for a steam turbine thermal power plant with an electrical capacity of 230 MW and a thermal capacity of 394 Gcal/h when switching to multigeneration mode due to additional production of hydrogen and oxygen using natural gas conversion methods and electrolysis method. The exergy of a thermodynamic system was determined by the amount of energy not characterized by entropy, which can be obtained by an external energy receiver from the system or supplied from an external source to the system during its
reversible transition from this state to a state of complete equilibrium with the environment [12]. The calculation method is described in detail in [12-14]. Exergy efficiency was determined by the formula:

\[ \eta_e = \frac{\sum E_{\text{out}}}{\sum E_{\text{in}}} \]

where \( \sum E_{\text{in}} \) and \( \sum E_{\text{out}} \) are the sums of exergies of the fluxes at the input and output of the system, respectively, MJ. During the calculations, the known dependences [1,13] were used to determine:

- exergy flow –
  \[ E_{\text{flow}} = G_{\text{flow}} \cdot \left[ \left( h_{\text{flow}} - h_0 \right) - T_0 \left( s_{\text{flow}} - s_0 \right) \right] \]
- exergy heat –
  \[ E_{\text{heat}} = q_{\text{heat}} \cdot \left( 1 - T_0/T_{\text{heat}} \right) \]
- exergy electricity –
  \[ E_e = N_e \]
- exergy fuel –
  \[ E_{\text{fuel}} = B_{\text{fuel}} \cdot \left\{ 1.04 \cdot Q_1^P + \left[ \left( h_{\text{fuel}} - h_0 \right) - T_0 \left( s_{\text{fuel}} - s_0 \right) \right] \right\} \]

where \( G_{\text{flow}} \) is the flow rate; \( h_{\text{flow}}, s_{\text{flow}} \) are the enthalpy and entropy of flow for given parameters; \( h_{\text{fuel}}, s_{\text{fuel}} \) are the enthalpy and entropy of fuel for given parameters; \( h_0, s_0 \) are the enthalpy and entropy of flow at environmental parameters; \( T_0 \) is the ambient temperature; \( q_{\text{heat}} \) is the heat input; \( T_{\text{heat}} \) is the temperature of heat input; and \( Q_1^P \) is the heat generated by burning fuel. In addition, the calculations used the known heat balance equations. The values of exergy and the calculation results of exergetic efficiency are given in table 1. \( E_{H2} \) is the exergy of produced hydrogen; \( E_{O2} \) is the exergy of produced oxygen; \( E_{H2O} \) is the exergy of water spent on the production of additional energy resources; and \( B_{\text{fuel}} \) is the fuel consumption. The exergy of energy produced was calculated by formulas (2) - (5).

### Table 1. Summary table of exergy values in different modes of operation of TPPs.

| Index | The value of exergy in the current mode | The value of exergy in the multigeneration mode | Dimension |
|-------|---------------------------------------|-----------------------------------------------|-----------|
| \( E_e \) | 4.377 \cdot 10^9 | 4.377 \cdot 10^9 | MJ |
| \( E_{\text{heat}} \) | 1.344 \cdot 10^9 | 1.344 \cdot 10^9 | MJ |
| \( E_{H2} \) | - | 27.528 \cdot 10^9 | MJ |
| \( E_{O2} \) | - | 0.129 \cdot 10^9 | MJ |
| \( \sum E_{\text{out}} \) | 5.721 \cdot 10^9 | 33.262 \cdot 10^9 | MJ |
| \( E_{\text{fuel}} \) | 17.401 \cdot 10^9 | 51.455 \cdot 10^9 | MJ |
| \( E_{H2O} \) | - | 7627 | MJ |
| \( \sum E_{\text{in}} \) | 17.401 \cdot 10^9 | 51.455 \cdot 10^9 | MJ |
| \( \eta_e \) | 32.9 | 64.6 | % |

When the TPP operates in the current mode, its exergy efficiency is 2 times higher than in the multigeneration mode.

The economic effect of hydrogen production for external sales for the same TPP was also estimated. Capital expenditures for additional equipment are estimated at 22.6 billion rub., with a hydrogen production capacity of 493 thousand Nm\(^3\)/h and 16.5 thousand Nm\(^3\)/h of oxygen. For the calculations, the following costs for hydrogen sales were taken: 100 rub/Nm\(^3\), 50 rub/Nm\(^3\) and 20 rub/Nm\(^3\). The results of the calculation of the volume of net present value (NPV) and payback period are presented in figure 2.

The calculation results show that the proposed technical solution is characterized by high economic indicators and can be implemented. However, there are risks associated with the promotion of new product “hydrogen” to the market. This indicates a high discount rate, decreasing the growth of NPV.

Overall criteria of the project implementation at various accepted costs of hydrogen based on the results of the economic analysis are given in table 2.
4. Conclusions
We have proposed a scheme of a multigeneration complex for high-energy facilities, supplemented by the production of hydrogen and oxygen. The transition of TES from the current mode of operation to the multigeneration mode, under the conditions adopted for the calculation, leads to a two times increase in the exergy efficiency of the station operation. The economic effect during the transition to multigeneration is characterized by a discounted payback period of 1.5 years from the start of equipment operation and an internal rate of return, IRR, of 60%.
The results obtained can be considered as an evidence of the thermodynamic and economic benefits of using the multigeneration mode at generation facilities.

Acknowledgments
The work was financially supported by the RF Ministry of Education and Science under the state contract within the competition of research projects of research teams of research centers and research laboratories of higher educational institutions (Application No. 13.3233.2017/PCh).

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