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Improving the Efficiency and Reliability of Existing and Future Russian GeoPP

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ABSTRACT

Russia develops, designs, manufactures and operates geothermal power plants (GeoPP). Geothermal power units with a total installed capacity of about 80 MW operate on the steam-hydrotherms of Kamchatka and the Kuril Islands. The fully automated Mutnovskaya GeoPP with a capacity of 50 (2x25) MW has been successfully generating electricity in Kamchatka since 2002.

To ensure efficient and reliable operation of the Mutnovskaya GeoPP power units, corrosion and deposits prevention methods based on the use of film-forming amines are developed/applied: octadecylamine during the scheduled maintenance period and helamine during the operation of the power units. The feasibility of increasing the efficiency of geothermal fluid utilization at existing and prospective Russian power plants based on the use of the combined geothermal power plant technological scheme with a binary cycle is being considered. The use of a hydrogen superheater to increase the energy potential of the saturated steam from the production well (primary steam) and flashed steam from separator (secondary steam) is planned. The operation of the hydrogen superheater is ensured by the utilization of excess electricity produced by GeoPP during the period of daily power reduction.

1. INTRODUCTION

Maintenance of design indicators of efficiency and reliability of the GeoPP during the operation period, as well as development and implementation of modern technological solutions when designing new GeoPPs and modernization of existing GeoPP are the main areas of work in the geothermal energy of Russia, Povarov and Tomarov (1995), Malyshenko et al. (2004), Malyshenko and Schastlivtsev (2010), Schastlivtsev et al. (2019). On the existing Russian geothermal power plants, methods are used to prevent corrosion and the formation of deposits through the use of film-forming amines. Trial tests of the helamine dosing system were carried out in the working circuit of the Mutnovskaya GeoPP to prevent the precipitation of impurities on the surface of pipeline elements and equipment.

In order to improve the efficiency and capacity of existing Russian GeoPP, various options of their modernization are being studied. Previously, a feasibility study was developed to increase the capacity of the Mutnovskaya GeoPP by means of the construction of a binary unit utilizing waste separate, Tomarov et al. (2016). Currently, research is underway to optimize technical solutions and technological schemes on the basis of the flashed steam overheating system use in combined GeoPP with binary cycle.

This paper presents some results of computational and analytical studies of the choice of the working fluid for binary cycle influence on the characteristics of a combined GeoPP with two separation pressures and superheating of secondary boiling water vapor using a hydrogen-oxygen steam generator.

2. PREVENTING DEPOSITS AND ENSURING RELIABILITY OF GEOTHERMAL POWER PLANT TURBINES

The use of turbines operating on saturated geothermal steam (geothermal turbines) is associated with problems stemming from the presence of a liquid phase with impurities in the turbine flow path, DiPippo (2015), Morris and Robinson (2015). The main specific features inherent in geothermal heat carrier include a relatively moderate heat potential, its being in single-and two-phase states, an increased content of salts, and significant corrosiveness, Tomarov et al. (2015), Semenov et al. (2002). All these features have a negative effect on the efficiency and reliability of the geothermal turbine's first and last stages.

Figure 1 shows a structural diagram reflecting the basic problems encountered in operation of GeoPP turbines that are connected with the geothermal steam quality and also the ways of solving them. The presence of a liquid phase (moisture) in geothermal steam is the main factor causing losses in the turbine stages, the occurrence of droplet impingement erosion in the last stage blades, and flow accelerated corrosion of the turbine flow path components.

The impurities arriving in the turbine together with the liquid phase facilitate the formation of deposits and intensify corrosion fatigue of the metal of turbine flow path elements. Noncondensable gases contained in the steam degrade the vacuum in the turbine condenser.

The energy losses in the flow path due to steam wetness cause an essentially degrading effect on the geothermal turbine efficiency. It should be noted that the content of moisture affects the turbine efficiency primarily due to increased loss of energy in the turbine cascades, loss for transporting dispersed (droplet) moisture and discrete (liquid film) liquid phase, and also loss caused by the deceleration effect of coarsely dispersed moisture on the rotor blades.

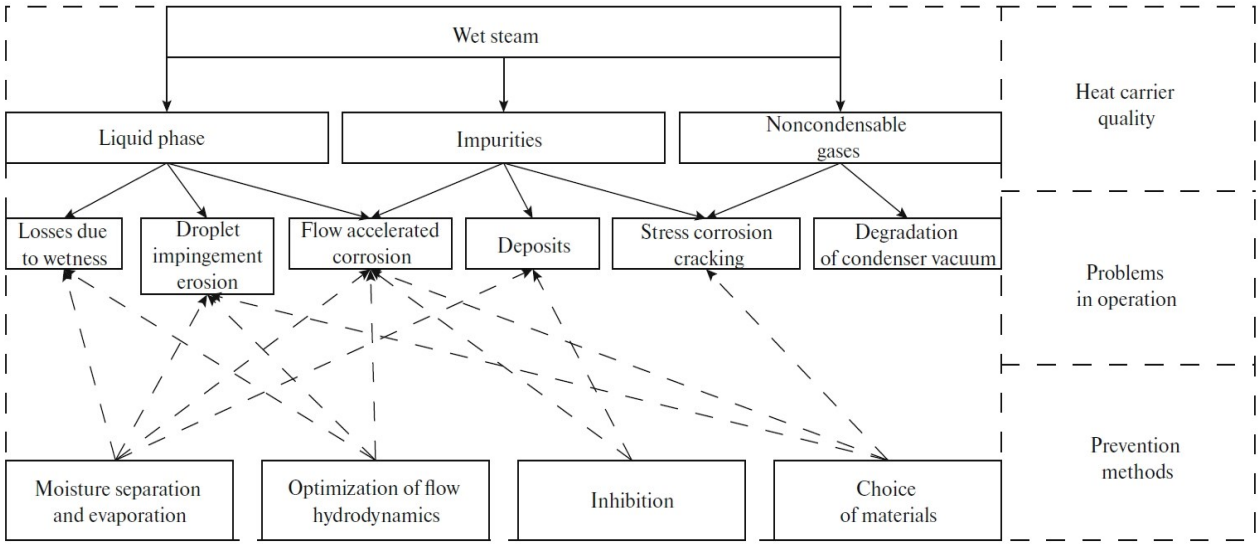


Figure 1: Effect of geothermal heat carrier quality on different metal damageability mechanisms' coming into the picture and degradation of vacuum in the condenser and methods for achieving more efficient and reliable operation of the GeoPP turbines.

The experience of the operation of the GeoPP has shown that significant reserves in raising the efficiency and reliability of power equipment lie in solving the issues of metal damage and the formation of deposits. To ensure efficient and reliable operation of the power units of Mutnovskaya GeoPP, methods for preventing corrosion and sedimentation based on the use of film-forming amines: octadecylamine during unit shutdown times and helamine during the operation of power units are developed / applied.

At Mutnovskaya GeoPP, the technology of periodic dosing of helamine into the geothermal coolant was tested. It has been established to reduce the amount of heat and it can reduce its intensity.

Dosing of helamine to the working circuit of Unit 1 of the Mutnovskaya GeoPP during 24 hours once per week was carried out through a second stage separator with concentrations in the geothermal steam up to 3-5 mg/kg. The results manifested in the turbine efficiency change were analyzed on the basis of Unit 1 operation parameters data.

Figure 2 presents some results of power data monitoring that mark the changes in the turbine efficiency during and after the helamine dosing period. The helamine dosing made it possible to increase for the certain period the turbine efficiency from 79,95 to 81,85%, i.e. by almost 2 %. The turbine efficiency upgrade caused to some degree by sediments washing effect, as well as improving of wet steam flow dynamics due to the metal surfaces hydrophobization and the dispersity of the drops reduction.

3. SECONDARY FLASH SUPERHEATING SYSTEM

For achieving more efficient and reliable operation of geothermal turbine units, it may be advisable to use an engineering system for supplying separated moisture secondary flash steam into the steam turbine low-pressure section in designing new or upgrading the operating combined-cycle geothermal power plants. Superheating of steam in a hydrogen steam superheater will help decrease the losses in the turbine resulting from steam wetness and exclude infliction of erosion damage to the last-stage rotor blades.

Figure 3 shows the basic process circuit of the system for preparing secondary flash steam at a GeoPP, which includes an electrolyzer for producing hydrogen and oxygen (the oxidizer) and a hydrogen steam superheater in which hydrogen is combusted in a steam–oxygen flow for heating secondary flash steam. The operation of the electrolyzer, which produces hydrogen and oxygen, is supported by the excess of electric energy generated by the geothermal power plant during its operation in the hours of its daily minimal load.

Owing to incorporation of the hydrogen steam superheater, the secondary flash steam enthalpy is increased to values at which steam expands in the turbine low-pressure section to the pressure in the condenser with a final wetness of no more than 2.0%. In addition, owing to admixture of the combustion products from the steam superheater into superheated steam, the superheated steam flowrate ($G_{s.s}$) can be increased by 3–5%.

One of the advantages of this process arrangement is the possibility to use excess electric energy generated in the minimum load hours for producing hydrogen and oxygen, which are then used in the system for preparing flash steam prior to supplying it to the turbine low-pressure section. As a result, it becomes possible, owing to reduced steam wetness, to increase the primary geothermal heat carrier utilization factor and to achieve more efficient and reliable operation of the steam turbine. Also, owing to secondary flash steam being additionally supplied to the turbine flow path, a higher turbine unit output is obtained.

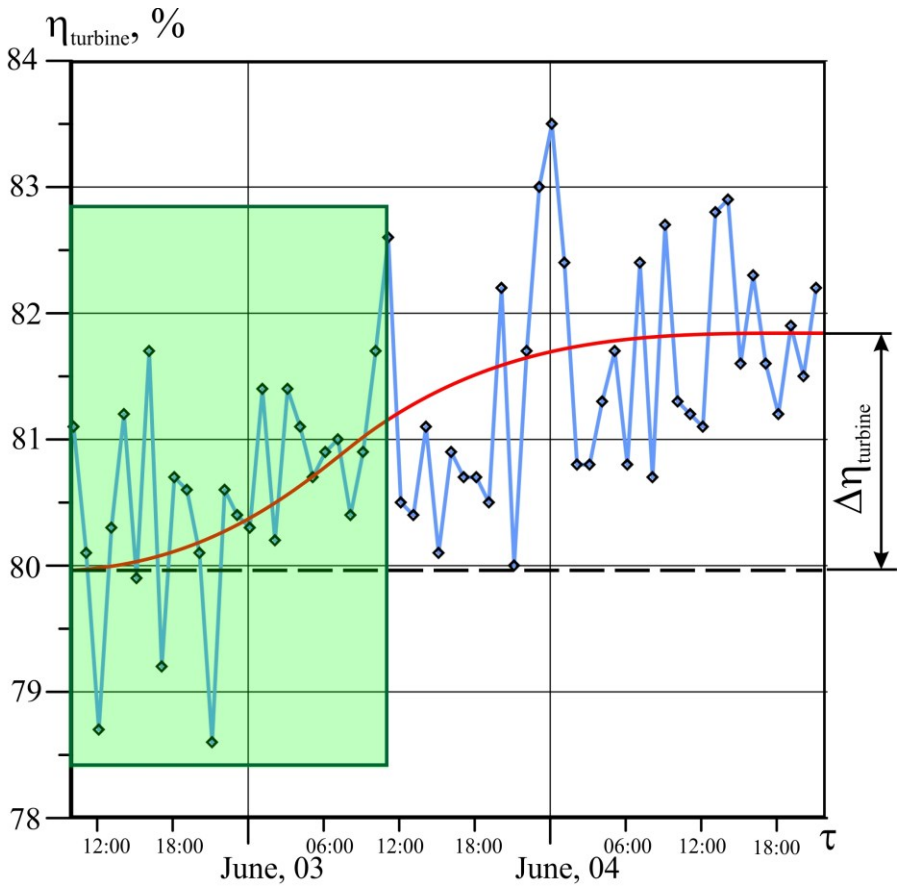


Figure 2: Increasing the Mutnovskaya GeoPP Unit 1 turbine efficiency while helamine dosing.

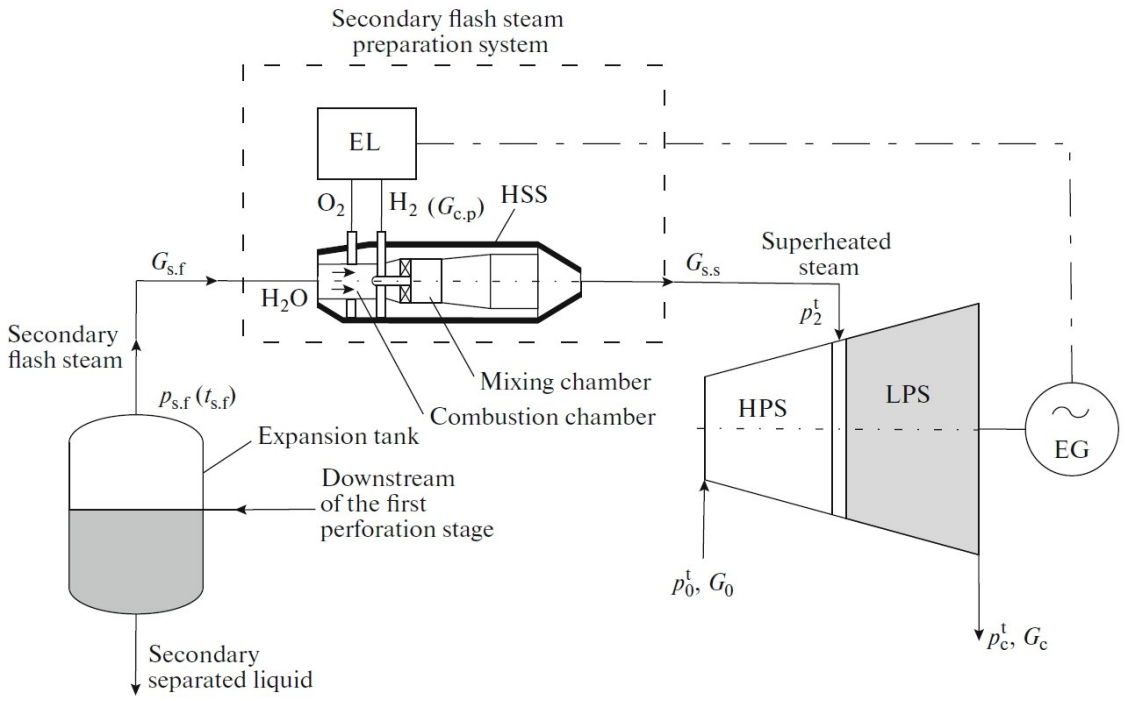


Figure 3: System for preparing secondary flash steam supplied through an intermediate inlet to the geothermal power plant turbine's low-pressure section. EL is the electrolyzer; HSS is the hydrogen steam superheater; EG is the electrical generator; HPS is the turbine high-pressure section; LPS is the turbine low-pressure section; $G_{s.f}$, $G_{s.s}$, and $G_{c.p}$ are the flowrates of secondary flash steam, superheated steam, and combustion products in the HSS; $p_{s.f}$, p^t_0, p^t_2, p^t_c are the pressures of secondary flash steam, steam at the turbine inlet, superheated steam upstream of the LPS, and wet steam in the condenser.

The h, s diagram shown in Figure 4 illustrates the variation of steam parameters in the geothermal turbine when the secondary flash steam is not used (the process a_1–a_2– a_2'), and also when it is supplied to the turbine low-pressure part (the process a_1–a_2–b_1–b_2). Secondary steam is superheated in its preparation system by means of a hydrogen steam superheater (the process a1–b1) so that the phase transition zone was in the area of the last stages during steam expansion in the turbine low-pressure section. As is seen from Figure 4, the admission of superheated secondary steam into the low-pressure section results in the fact that almost the entire low-pressure part of the turbine operates in the steam single-phase state region.

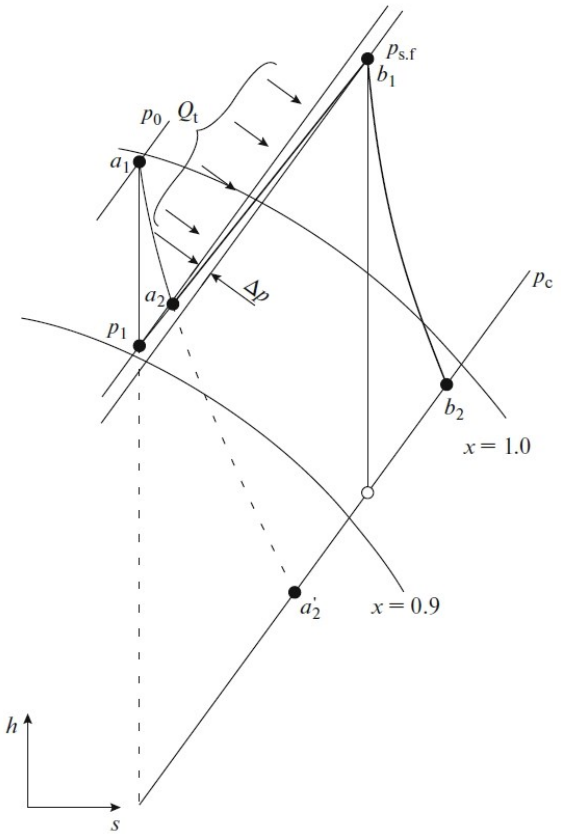


Figure 4: Variation of steam parameters in the geothermal turbine without using secondary flash steam (a_1–a_2– a_2') and with using secondary flash steam for organizing its intermediate admission to the turbine low-pressure part (a_1–a_2–b_1–b_2) with heating it by means of a hydrogen steam superheater (a_1–b_1). Qt is the heat supplied in the hydrogen steam superheater to the working medium; Δp is the pressure loss in the secondary flash steam preparation system; and p_0, p_1, $p_{s.f.}$ and p_c are the pressures of steam upstream of the turbine, downstream of the HPS, upstream of the LPS, and in the condenser.

4. NUMERICAL MODELING OF A COMBINED CYCLE GEOTHERMAL POWER PLANT WITH SECONDARY FLASH SUPERHEATING SYSTEM

Based on the simulation of the GeoPP technological circuit (the scheme is shown in Figure 5), computational studies were performed for selected as a result of optimization studies in Tomarov et al. (2016) working fluids from the following groups of organic substances: non-toxic fire and explosion safe (group №1), low toxic fire and explosion safe (group №2), non-toxic flammable (group №3), low-toxic flammable and explosive (group №4).

Computational studies have shown that the use of superheating of flashed steam using hydrogen-oxygen steam generator allows more than twice to reduce the degree of humidity of steam at the outlet of the turbine. In addition, this makes it possible to have superheated steam at the inlet to the low-pressure part of the steam turbine in comparison with the variant of the GeoPP technological scheme without flashed steam overheating. At the same time, it should be noted some increase in the degree of steam humidity at the turbine outlet with an increase in the pressure in the expander.

One of the main tasks of the computational studies was to determine the effect of various organic fluids on the efficiency and power of the binary cycle as part of the combined cycle GeoPP with flashed steam overheating. The calculated values of the efficiency (net) of the binary cycle of this GeoPP using different working fluids are shown in Figure 6. The highest values of efficiency (net) are close to 12% and obtained using the following working fluids R-236fa, R-227ea, R1318, RC-318, R-134a, R-227ea and R31-10. The lowest efficiency value (net) of the binary cycle relates to the use of organic fluids R-218 and R-143a, which are 6.0% and 7.8%, respectively. The efficiency values (net) of the binary installation when using the rest of the considered working fluids lie in the range of 8,8 - 10,4%.

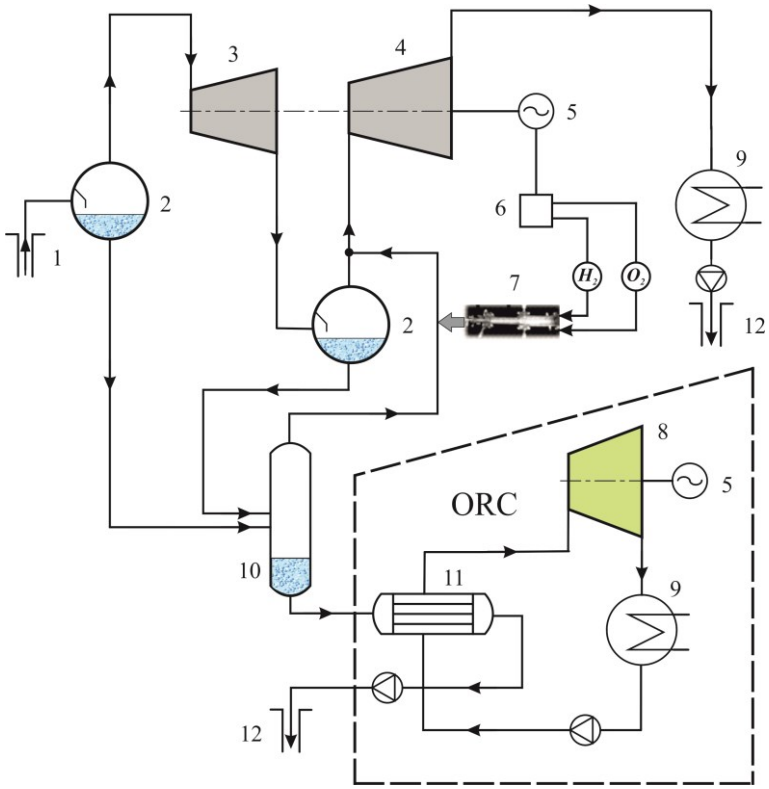


Figure 5: The principal technological scheme of a combined cycle double flash GeoPP with superheating of flashed steam in hydrogen-oxygen steam generator: 1 - production well; 2 - separator; 3 - high pressure part of steam turbine; 4 - low pressure part of steam turbine; 5 - electric generator; 6 - electrolyzer; 7 - hydrogen-oxygen steam generator; 8 – organic Rankine cycle (ORC) turbine; 9 - condenser; 10 - expander–separator; 11 - evaporator; 12 - reinjection well.

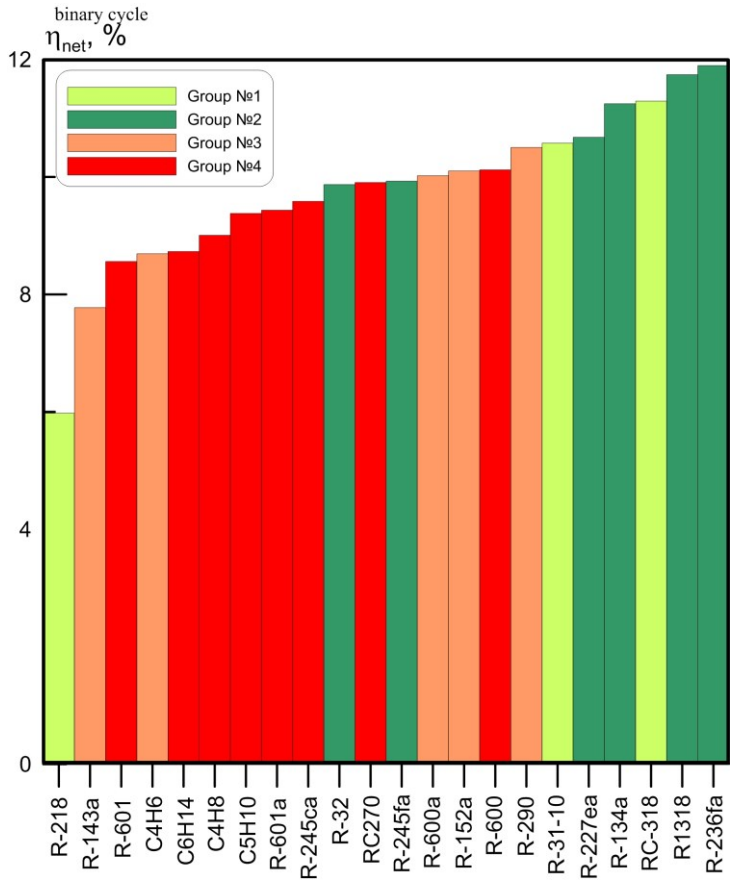


Figure 6: Histogram of calculated values of the efficiency (net) of a binary GeoPP unit of a combined binary cycle using various organic working fluids.

Studies have shown that the power values of the binary cycle of combined GeoPP of more than 12.0 MW occur when using the following working fluids: R-227ea, R31-10, RC-318, R-134a, R-236fa and R-1318, and the lowest values (less than 5.2 MW) correspond to application as working fluid C4H6, C4H8, C5H10, R-601, C6H14 and R-218. It should be noted that the best values of efficiency and power of the binary cycle of combined GeoPP are achieved using working fluids belonging to above-mentioned groups №1 and №2.

The highest net power values of the combined cycle GeoPP with two separation pressures of geothermal fluid and secondary flash steam superheating using a hydrogen-oxygen steam generator are achieved while using R-31-10, R-227ea and RC-318 as working fluids (Figure 7). At the same time, the optimal design pressure in the expander-separator, which ensures the highest efficiency and power is equal to 0.47 MPa.

Depending on the choice of the working fluid, the power of the combined GeoPP with organic Ranline cycle may change by 5.0%. At that, the optimal pressure in the expander-separator may vary in the range of 0.2-0.47 MPa. The lowest power values of this GeoPP correspond to the use of organic fluids from group №4.

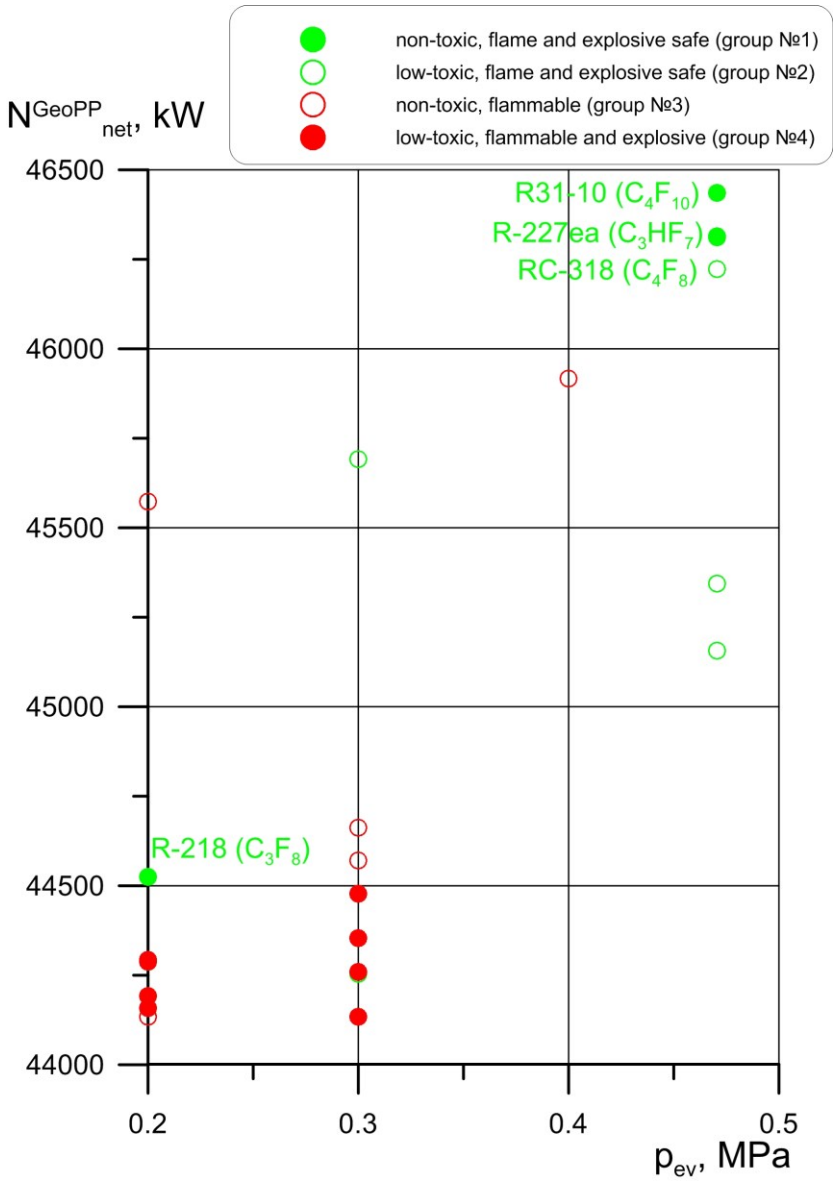


Figure 7: Calculated values of power (net) of the combined-cycle GeoPP for working fluids of various groups depending on the pressure in the expander-separator.

When solving optimization problems on the choice of working fluid for combined GeoPP with organic Rankine cycle, it is reasonable to use multi-axis diagrams of parameters and characteristics relative values. Figure 7 shows such a diagram for working fluids R-290, R-227ea, R-3110, R-32, RC-318 and C_5H_{10} used as working fluids in combined GeoPP with organic Rankine cycle and flashed steam overheating system. Such diagrams help to compare the characteristics relative values for different organic working fluids, carry out their comparative analysis and make proved decision on the choice of the working fluid, taking into account the stated priorities (safety, economic and ecological criteria etc.).

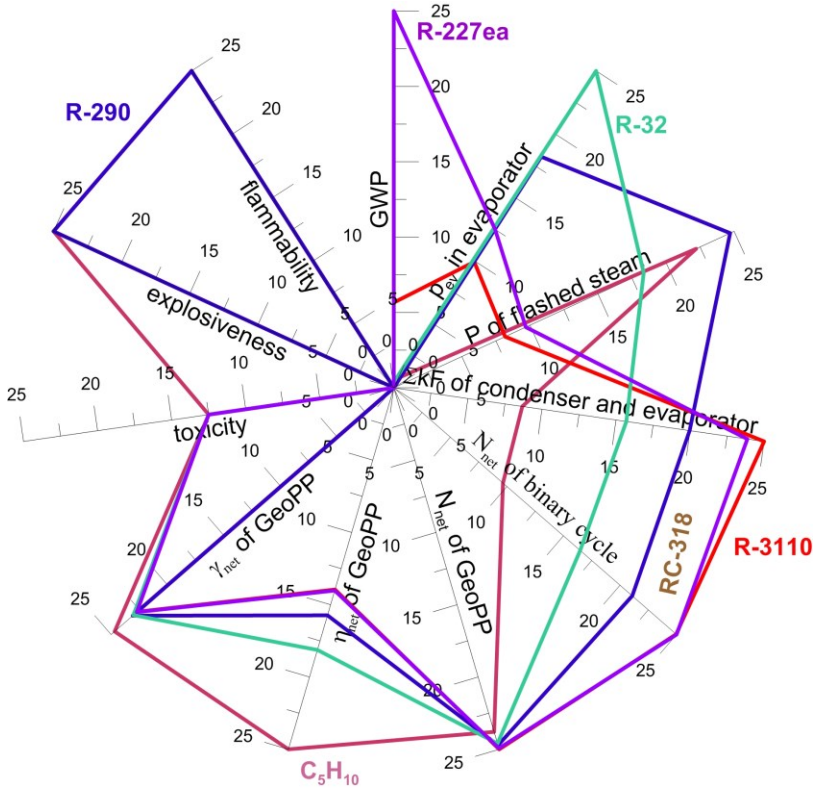


Figure 8: Multi-axis diagrams of the parameters and characteristics relative values for a combined-cycle GeoPP with R-290, R-3110, R-32, R-227ea, C_5H_{10} and RC-318 as a working fluid.

CONCLUSION

Computational studies have been performed to determine the effectiveness of the use of the flashed steam overheating system using a hydrogen-oxygen steam generator in the technological circuit of the combined GeoPP with binary cycle. Results of modeling have shown that the use of overheating of flashed steam using a hydrogen-oxygen steam generator provides for an increase in the efficiency of the flow section of the steam turbine by reducing the moisture content of the steam by more than two times. The use of methods for the prevention of corrosion and the formation of deposits using film-forming amines makes it possible to maintain the operating efficiency of the Mutnovskaya GeoPP close to the design indices.

Optimization studies have shown that the largest values of power and efficiency of a binary installation, which is part of the GeoPP combined binary cycle with the lowest specific consumption of separate are achieved when organic substances from the following groups are used as a working fluids of binary cycle of combined GeoPP: non-toxic fire-and-explosion-proof (R31-10 and RC-318) and low-toxic fire and explosion-proof (R-227ea, R-236fa, R1318 and R-134a). The results of numerical modeling are useful for use at the design and modernization stages of GeoPP utilizing steam hydrothermal sources.

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