DEVELOPMENT OF TECHNOLOGIES FACILITATING THE TRANSITION TO RENEWABLE ENERGY SOURCES: OPPORTUNITIES FOR APPLICATION OF REACTIVE HYDRO-STEAM TURBINES FOR LOW-POTENTIAL HEAT RESOURCES

Oleg Milman[1,2*], Viktor Perov[1], Petr Ananyev[1]

[1]Turbokon Research and Production Innovation Enterprise, 43 Komsomolskaya roshcha str., Kaluga, 248010, Russia*
[2]K.E. Tsiolkovsky Kaluga State University, 26 Stepana Razina str., Kaluga, 248023, Russia*

[*]Corresponding Author Oleg Milman, email: milman.o.o@mail.ru;

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ABSTRACT

The study discusses the opportunities for producing geothermal energy, which is a renewable resource providing a continuous supply of heat from the Earth's interior. Unlike fossil fuels, which are non-renewable and cause environmental degradation, geothermal energy is of great interest to researchers, particularly in the context of sustainable development principles. The authors demonstrate the advantages of a new hydro-steam turbine (HST) using the heat of water from geothermal springs and heating boilers for power generation. The HST is designed as a Segner wheel with a steam-water mixture flowing out of a Laval nozzle, the resulting reactive force driving the turbine rotor and the power generator. The features of the HST thermodynamic process are analyzed in the form of a case study describing the design of a 20 kW plant and providing the technical specifications of the installation for a heating boiler plant: hot water flow rate of 7 kg/s, temperature of 130°C, and inlet pressure of 0.6 MPa. The authors present the thermal schemes of the HST in two variants (at a boiler house and as a part of a geothermal power plant). The study concludes that the main advantages of the HST are the absence of elements subject to erosion under the action of steam and water flow and the simplicity of the design increasing the availability of geothermal energy for power generation. Among the limitations of the HST is its low economic efficiency narrowing down its application to conditions where geothermal fields are available for local power supply.

Keywords: steam-water mixture, nozzle, temperature, pressure, rotor, boiler house, GeoPP, separation, condensation.

INTRODUCTION

The use of low-potential heat in the form of hot water is an avenue for power generation without fuel consumption. However, the advantages of this power generation method and the importance of research in this area are not limited to the need to switch to renewable energy sources that do not deplete natural resources (Shilnikova, 2023) or deteriorate the environment (Plotnikov et al., 2024).

Geothermal energy can provide a constant and reliable supply of electricity, known as baseload power (Asadulagi et al., 2024). As opposed to solar and wind power, which are intermittent and weather-dependent, geothermal power plants can operate continuously, providing a stable and predictable energy supply (Bezpalov et al., 2023). As noted by researchers, turbines have much lower lifetime operation and maintenance costs (Bai et al., 2023; Gabayan, 2021; Seyyed, 2024) compared to fossil fuel-fired turbines. Particularly noteworthy is the possibility of a hybrid approach: geothermal sources and heating boilers can be deployed in combined heat and power (CHP) systems that simultaneously produce electricity and useful thermal energy from a single energy source (Prestipino et al., 2022). This dual generation increases overall efficiency and can provide heating for buildings, industrial processes, and district heating systems. This contributes to energy security by diversifying the energy mix (Avdeev et al., 2024) and reducing dependence on fossil fuels (Kayesh, Siddiqa, 2023). The presence of a hot water source means an opportunity to produce energy relatively independently minimizing geopolitical risks (Kryshtanovych et al., 2024).
Our research focuses on exploiting hot water springs with a temperature of 100-150°C as part of Russian geothermal deposits (Kamchatka, Kuril Islands, Caucasus). Using these sources, installations based on the organic Rankine cycle (ORC) can be effective, but their production has not yet been launched in Russia. This is due to the fact that these installations require substantial monetary investments. Initial capital investment in the equipment and infrastructure for ORC systems can be substantial (including the cost of turbines, heat exchangers, pumps, and consumables). ORC systems can be tricky to operate and maintain. The technology involves precise control of temperature, pressure, and flow rate. The technical maintenance of components, especially turbines and heat exchangers, drives people away from developing ORC systems. For this reason, we turned to an alternative to the ORC – the hydro-steam turbine (HST). The HST's leading advantage (Favorskii et al., 2002) is its simple design and the absence of elements of the flow section washed by the steam-water mixture, which is not subject to erosive wear. The HST's disadvantage is low efficiency partly compensated by the cogeneration mode. This study aims to establish and substantiate the effectiveness of a reactive HST for low-potential heat resources with different application schemes.

MATERIAL AND METHODS

Data for Analysis

To achieve the research goal, we performed calculations and developed the design of a pilot HST with a capacity of 20 kW. Further, we substantiated the use of the turbine for two main variants of HST utilization: at heating boilers in a cogeneration scheme and at geothermal fields. The geothermal field variant used waste heat from the GeoPP separator (Kamchatka territory) for power generation.

Operation Principle

The reactive HST using hot water energy (Figure 1) designed as a Segner wheel is distinguished by a simple design and manufacturing process (Milman et al., 2002; Shevelev et al., 2007).

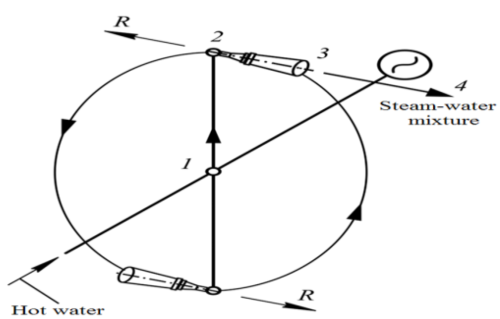

Figure 1. Principal scheme of HST operation.

Hot water at a temperature of 100-150°C is fed to the center of the HST shaft and then supplied through radial channels to the Laval nozzles, where it boils and accelerates from the expanded part of the nozzle and flows into the surrounding space, where low pressure is maintained. The flow of the mixture in the amount G at a speed W creates a reactive amplification $R=GW$, which drives the generator's rotor into rotation and enables the generation of electrical energy.

Thermodynamic Aspects

Figure 2 shows thermodynamic diagrams of the HST process compared to the classical Rankine cycle on water.

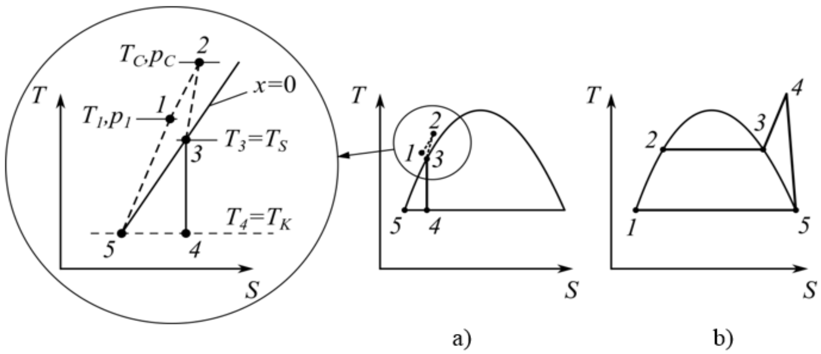

Figure 2. Diagram of the cycles: a) – HST, b) – ORC.

In the HST cycle, water at temperature T_1 and under pressure $P_1 > P_s$ (where P_s is saturation pressure at T_1) is supplied to the HST rotor (point 1). In radial channels, the water pressure increases to a value of P_C^1 (with minimal a minimal shift in temperature $\delta T = T_C - T_1$).

At the inlet to the Laval nozzle (here there is a geometric similarity in that it is an underheated liquid with boiling, not a gas or vapor, that flows out (Tonkonog et al., 1997)) the flow accelerates in the narrowing section with pressure dropping to point 3 (saturation state $T_3 = T_s < T_1$). Next, boiling occurs with the formation of a vapor-water mixture and its acceleration in the expanding part of the nozzle [2÷4]. During the expansion process, the pressure of the mixture is reduced to the pressure in the HST casing (point 4), and flow acceleration creates a reactive force R in the direction opposite to the velocity vector of the vapor-water mixture flowing out of the nozzle. In the condenser connected to the steam space within the HST casing, the heat of the exhaust steam is removed. In cogeneration schemes, this heat is used for useful heating (make-up water, heating network, etc.).

Increasing water pressure in the radial channels as it moves from the center to the nozzles requires energy input (Fedorov et al., 2002). This energy is taken away from the total HST energy generated by the rotor and partially (after deducting losses) returns to the HST cycle when the water flows out of the narrowing part of the nozzles (Milman and Goldin, 2003).

RESULTS

HST design Features

Figures 3-5 summarize the main technical solutions adopted for this turbine.

Figure 3 gives a general view of the HST with the generator and separator.

A volumetric separator 5 for separating steam from the steam-water mixture is installed under the casing; the side wall of the separator has a window for steam discharge to the surface condenser.

The synchronous generator 2 is connected to the rotor by a pin coupling, and the generator and turbine are mounted on a rigid frame 4 to ensure reliable alignment.

The cantilever rotor with four Laval nozzles rotates inside the HST casing (Figure 4).

Working water is supplied through stop valve 3 via a DN65 pipeline to the center of the rotor, which rotates in the seal block.

The supply of water to the radial channels is designed with the profiling of the inlet edges by the principle of a centrifugal pump.

Nozzles on the rotor (Figure 4) are turned 15° away from the wheel's rotation plane to prevent the steam-water mixture jet from a given nozzle from flowing onto the mounting elements of the neighboring nozzle [5÷8].

The exit of the rotor from the casing to the bearings and onto the generator passes through a sealing system with three intermediate chambers (Figure 5). The first one is supplied with condensate from the pump, the third one – with air under the pressure (overpressure) of 3-5 kPa, and the middle one is used to drain the air mixture. This system prevents air from entering the vacuum zone and water from entering the rotor bearings.
The pressure inside the turbine casing (vacuum) is maintained by a surface condenser cooled by network water from the heating system.

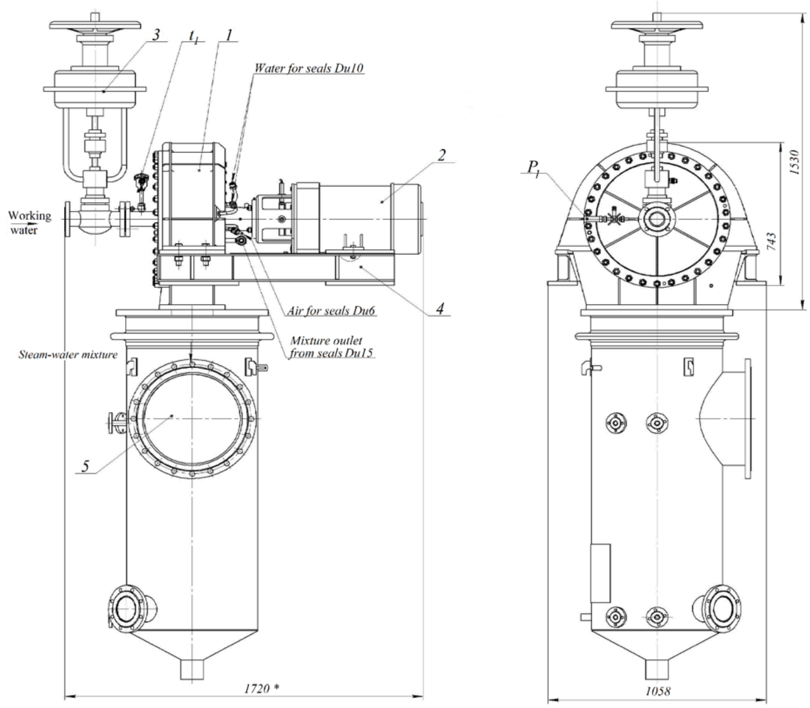

Figure 3. General view of HST-20 equipment.
1 – HST, 2 – generator, 3 – stop valve, 4 – frame, 5 – separator

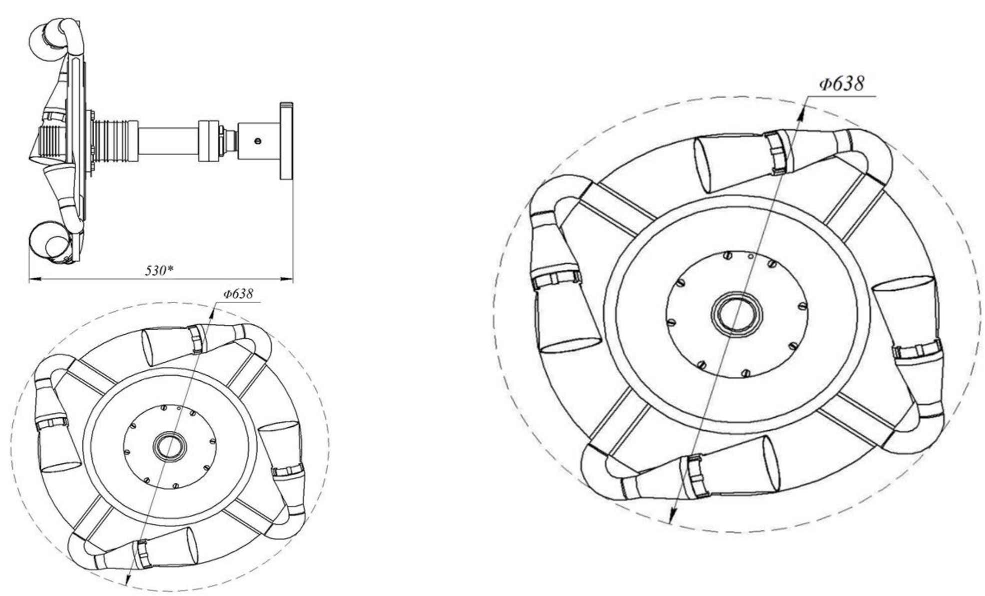

Figure 4. HST-20 rotor.

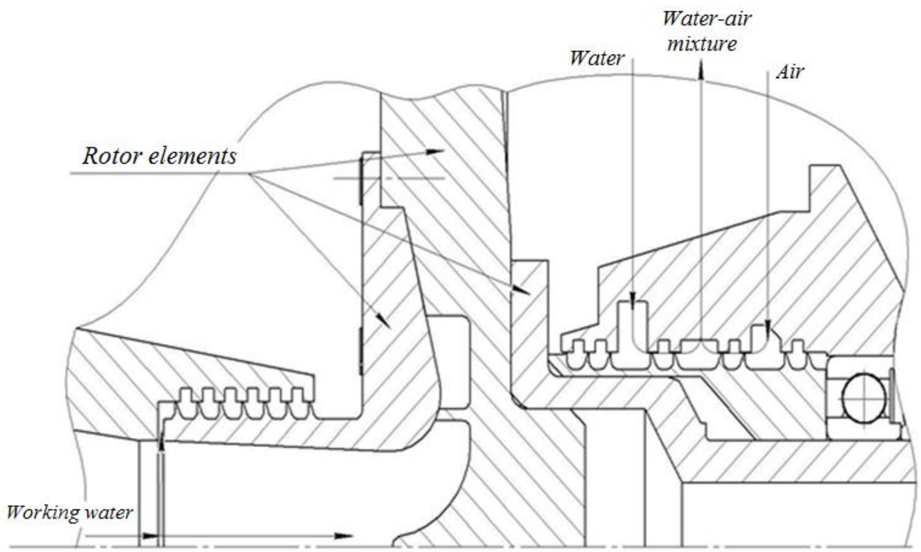

Figure 5. Turbine labyrinth seal

Schemes of HST Application at Heating Boiler Plants
The principle scheme of HST operation as part of a boiler house is given in Figure 6.

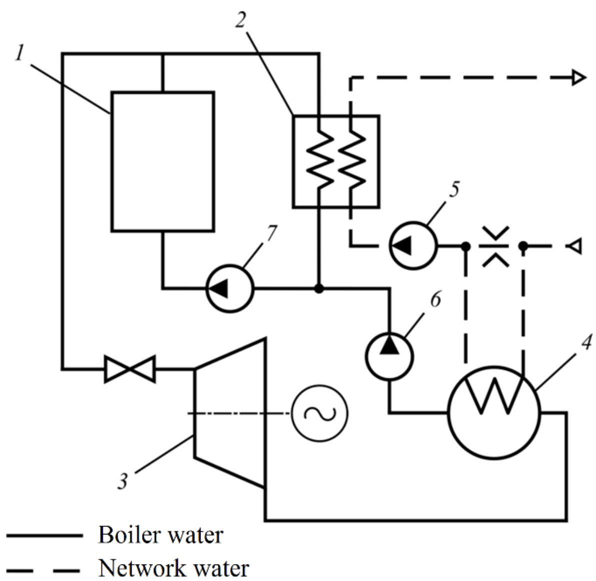

Figure 6. HST at a heating boiler plant.
1 – water boiler, 2 – network water heater, 3 – HST, 4 – condenser, 5-7 – pumps: network, condenser, and boiler.

The water boiler operates with an outlet water temperature of 110-150°C, heating supply network water in accordance with the temperature schedule of the heating network. Part of the boiler water is withdrawn to the HST, producing useful work. The exhausted steam is condensed in the condenser by return network water, and the condensate then returns to boiler water.
Thus, there is no loss of boiler water heat to the environment, as it is almost entirely transformed into the boiler room scheme.
The technical specifications of HST-20 for heating boiler plants are provided in Table 1.

Table 1. Technical specifications of HST-20.

Power at the generator terminals, kW	20.5
Working water flow rate, kg/s	7.02
Working water temperature, °C	130
Working water pressure, MPa	0.6
Pressure behind the turbine, kPa	30
Cooling water flow rate, kg/s	110
Cooling water temperature, °C	57
Cooling water pressure, MPa	0.45

A similar scheme at a steam boiler house confirmed (Milman, 2000) that specific fuel consumption for power generation amounts to 0.145-0.150 kgf/kWh.

Another option for utilizing the heat from the geothermal steam separation is shown in Figure 7.

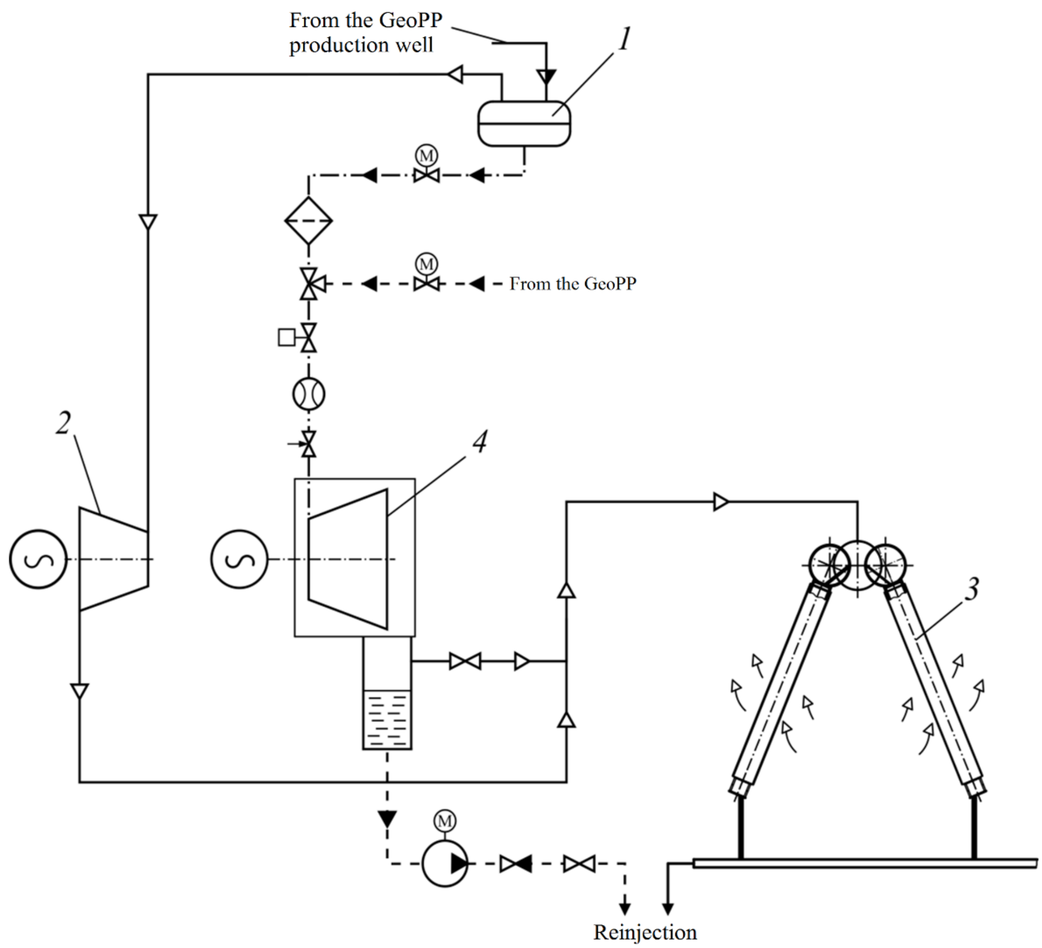

Figure 7. HST at a GeoPP

1 – steam preparation system, 2 – GeoPP turbine generator, 3 – GeoPP condenser, 4 – HST

From the GeoPP steam preparation system 1, the separates are taken to HST 4 operating in parallel with the main turbine generator 2. The exhaust steam from the HST is discharged to the main condenser 3, and the separate is discharged to the reinjection wells.

This scheme uses the waste heat from the GeoPP separates to generate electricity.

Discussion

Our findings suggest that the main advantage of the HST is the simplicity of its design and the absence of erosive wear processes in the plant elements. These advantages fit well into the cogeneration scheme at the boiler plant and GeoPP (Barilovich et al., 1987; Fedorov et al., 2009).

In cogeneration mode, the specific consumption of fuel equivalent does not exceed 150 gf/kWh. HST units at geothermal power plants allow the use of separates from the steam treatment system for generating additional power.

Analyzing the market for HST at a power level of 50-150 kW shows that they can be organically integrated into the schemes of hot water boiler plants and operate in cogeneration mode, displacing electricity from the power system due to their low cost and ease of operation. Our study aims to build on the advances in geothermal technologies such as binary cycle power plants, which allow producing electricity from lower-temperature geothermal resources. This expands the possibilities for geothermal power generation and makes it viable in different regions across the globe.

Prospective continuation of our research can address the possibilities of enhanced geothermal systems (EGS) extending the use of geothermal energy to areas with limited geothermal resources (van der Zwaan et al., 2019). In EGS, water is injected into hot rock formations, creating artificial geothermal reservoirs. This technology has the potential to greatly increase the availability of geothermal energy for power generation.

CONCLUSIONS

The production of electricity from hot water using geothermal sources and heating boilers is needed for environmental sustainability, energy efficiency, economic benefits under certain conditions, and improved energy security. The continuous and reliable nature of geothermal energy in combination with technological possibilities (the presented utilization schemes) significantly increases the opportunities to transition to renewable energy sources in the territories where hot water sources with a temperature of 100-150°C are available as part of geothermal deposits.

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