УДК 669.2

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https://doi.org/10.32347/2409-2606.2025.55.115-127

THERMODYNAMIC ANALYSIS OF THE EFFECTIVENESS OF THE THERMAL SCHEME OF GEOTHERMAL POWER PLANT

Abstract. *Quoted results of numerical studies of the effectiveness of the thermal scheme of geothermal power plant. Researched subcritical and supercritical Rankine cycles with different working substances such as pure and mixtures in the temperature range 70...130 °C. Exposed effect of operating parameters: temperature and pressure of the steam before and after the turbine, heat exchange efficiency in the evaporator and condenser and ambient temperature. Specified dependence of the electrical power from the coefficient of performance of the power plant. The calculation of the power generated by the power equipment and the utilization of the heat of the geothermal fluid were carried out. The electrical power generated depends on the temperature of the geothermal fluid and varies from thermal evaporation. It is shown that each working fluid is effective in a certain temperature range. The use of a variety of working fluids provides a variety of cycle utilization rates by geothermal power plants.*

Keywords: *geothermal energy, geothermal power plant, refrigerant, binary cycle.*

Introduction. There is an annual global increase in the installed capacity of geothermal power plants of 10-20%, and their total capacity in 2023 is 16318 MW on 198 geothermal fields [1]. Efficient conversion of geothermal energy into electricity requires the development of specialized power equipment. Conventional power plants operate on water vapour (steam turbine at a pressure of 0,5-0,7 MPa) are not suitable at temperatures of the heat source of low density and accordingly a large size of the turbine. Use of low-boiling working fluids allows for reducing the size of the turbine.

Research relevance. The portion of renewable energy should be significantly increased in the framework of the European Green Deal. Most of the sources are weather-dependent, which causes instability of power grids. But geothermal energy is constantly available. Thus, such sources should be exploited at the available places.

Recent studies and publications. Geothermal power systems are widely used power plants with the Organic Rankine cycle (ORC) binary cycle (Fig. 1).

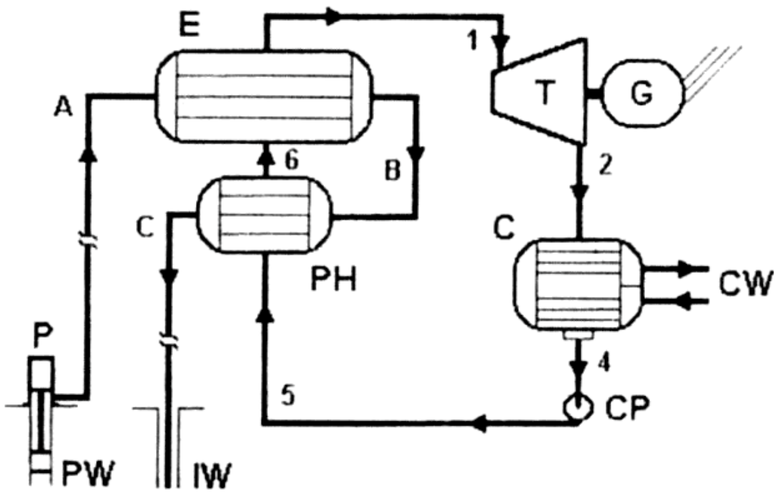

Fig. 1. Heat scheme of binary station [2]:
PH – pre-heater; E – evaporator; T – turbine; C – condenser; CP – condensate pump; PW – production well(s) – the source for geothermal water; IW – injection well – return of the cooled geothermal water; A-B-C – geothermal water loop; 1-2-4-5-6 – organic motive substance loop; CW – cooling water loop

Organic motive fluid of geothermal power plant in the binary cycle receives heat from geothermal water (brine), evaporates, expands in the turbine, condenses and returns via condensate pump to the evaporator. Currently, binary stations are widely used. In 2023, 25.1 % of all operating geothermal power is generated on the binary stations [1].

Analysis of the world's geothermal resources shows that dominant geothermal fields with edge water give temperatures below 150 °C. In Ukraine, there are also geothermal fields with a temperature of 150–180 °C, stocks of which can produce about 200 MW of electricity. However, most of the fields are characterized by temperature conditions below 130 °C.

At a temperature of heating medium 65–150 °C, it's difficult to build a steam power plant, which may have effective economic parameters. As international experience shows, lowering the temperature of the geothermal source requires more sophisticated technologies [1, 3].

The aim of the paper is to find the conditions of effective power generation using geothermal energy.

Condition of the problem. An important characteristic of the organic motive substance for the plant is a binary form of saturated steam curve, shown in Fig. 2 in the coordinates P-H (temperature-enthalpy).

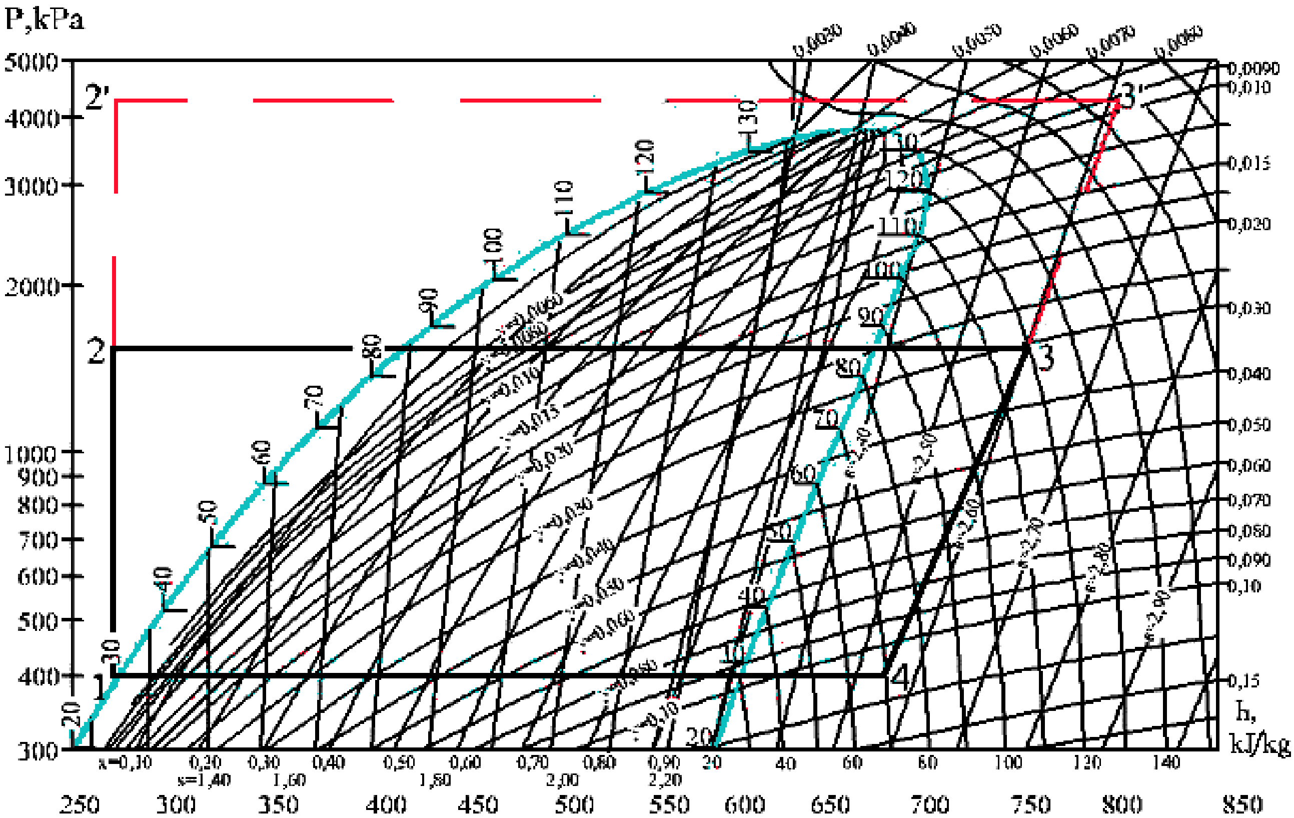

Fig. 2 Diagram"pressure-enthalpy" of the binary cycle of a geothermal power station

The curve of the vapour of water has a positive slope, and some hydrocarbons and Freon show a negative bias to the saturated vapour line segments.

Processes of steam expansion in the turbine in the Rankine cycle are shown by curves 3-4 and 3'-4. For some substances, the working process of steam expansion occurs from the saturated vapour line to superheat the water requires a considerable degree of superheat to avoid significant moisture in turbine exhaust (condition 4).

In the first approximation, the mass and dimensions of the turbine determine its value, and the size of the value can be estimated from the area of the exit section of the steam turbine:

$$F=\frac{W}{h_1-h_2}\cdot\frac{v_2}{k\cdot a_2}\ [\mathrm{m}^2]; \tag{2}$$

where W – turbine capacity, kW; h_1 and h_2 – starting and final enthalpy during steam expansion, kJ/kg; v_2 – specific volume of steam after expansion, m^3/kg; k – a factor; α_2 – speed of sound in the organic motive substance at the turbine outlet, m/s.

By determining the change in energy and speed of sound at the outlet of the turbine, the relative cross-sectional area and thus the relative sizes of turbines can be determined.

Simulation technique. The equipment of the geothermal power plant is calculated. The capacity of the pump is determined by the relationship:

$$N=\frac{\left(P_{fl,out}-P_{fl,in}\right)\cdot m_{fl}}{\rho_{fl}\cdot\eta_p}\ [\mathrm{W}] \tag{2}$$

where $P_{fl,out}$ and $P_{fl,in}$ – pressure at the outlet and inlet of the pump [kPa]; m_{fl} – pumped fluid flow, [kg/s]; ρ_{fl} – density of the fluid [kg/m^3]; η_p – adiabatic efficiency of the pump.

The calculation of the turbines is made by the adiabatic model. As the initial data the flow pressure P_{in} [kPa] and temperature T_{in} [K] at the turbine inlet, the flow pressure P_{out} [kPa] and temperature t_{out} [K] at the turbine outlet, organic motive substance flow rate m [kg/s] and adiabatic efficiency of the turbine η are used

Enthalpy of the organic motive substance is determined by the parameters:

$$h_i = \mathrm{h}(P_i, T_i)\ [\mathrm{kJ/kg}]. \tag{3}$$

Then the power generated in the ideal turbine under an adiabatic expansion process is:

$$N_{id} = (h_{out} - h_{in})\cdot m\ [\mathrm{kW}]. \tag{4}$$

Net power from the shaft of the turbine

$$N = N_{id}\cdot\eta\ [\mathrm{kW}] \tag{5}$$

Enthalpy at the turbine outlet in the real process (including losses) is defined as

$$h_{out} = h_{in} - (N/\mathrm{m}) \ \ [\mathrm{kJ/kg}], \tag{6}$$

which makes it possible to calculate the temperature of the steam at the turbine outlet.

For determining the parameters in the counterflow heat exchanger in our formulation of the problem (i.e. excluding the pressure losses and heat losses to the environment), a system of three equations was used:

$$\begin{cases} Q = m_{hot} \cdot \left(h\left(T_{hot,in}\right) - h\left(T_{hot,out}\right)\right) \\ Q = m_{cold} \cdot \left(h\left(T_{cold,in}\right) - h\left(T_{cold\,out}\right)\right), \\ Q = k \cdot F_{xchg} \cdot \Delta T \end{cases} \tag{7}$$

where m_{hot}, m_{cold} – mass flow rate of the hot and cold heat transfer fluids, respectively [kg/s]; $T_{hot,in}$, $T_{hot,out}$ – temperature, respectively, at the inlet and outlet of the hot heat transfer fluid [K]; $T_{cold,in}$, $T_{cold,out}$ – temperature, respectively, at the inlet and outlet of the cold heat transfer fluid [K]; F_{xchg} – heat exchange surface area; k – average heat transfer coefficient of the heat exchanger [W/(m^2·K)]; ΔT – average value of the temperature difference of the heat exchanger.

To find the mean value of the temperature difference of the heat exchanger, the following correlation is used:

$$\Delta T = \frac{\left(T_{hot,in} - T_{cold,out}\right) - \left(T_{hot,out} - T_{cold,in}\right)}{\ln\left(\dfrac{T_{hot,in} - T_{cold,out}}{T_{hot,out} - T_{cold,in}}\right)} \ [\mathrm{K}]. \tag{8}$$

The presence of the regenerative heat exchanger, in which the heat of geothermal water at the evaporator outlet (or steam turbine) is given for heating the low-temperature coolant to the evaporator, reduces the thermal load on the evaporator and condenser. As the results of the performed research [3], we'll obtain a maximum net electrical power is achieved by increasing the flow of geothermal water, geothermal circulating in the circulation system, and optimizing the parameters of the thermodynamic cycle of the secondary circuit. The process of steam expansion in the turbine is regarded as adiabatic. Calculation of steam expansion in a polytropic process is associated mainly with the technical perfection of the process equipment.

Results of the research. As it was mentioned earlier, now there are environmentally friendly ozone-friendly substances of a new generation – freon ethane, propane and butane series. The prospect of their use as an organic motive substance for the cycle of a geothermal energy converter into electricity has been studied in this work. Numerical study of Rankine cycle of the geothermal power plant with a binary cycle was performed with different working substances (R12, R13, R13b1, R22, R114, R134a, R142b, R143a, R152a, R218, R318).

Calculations of thermodynamic parameters of the Rankine cycle were performed under the following conditions:

- adiabatic efficiency of the turbine η = 0.70 - 0.80;
- efficiency of pump η_p = 0.75 - 0.80;
- ambient temperature is 288,15, 293,15, 298,15 K (plus 15, 20, 25 °C).
- ΔT = 5, 10, 15 K approach in the regenerative heat exchanger and evaporator (minimum temperature difference between water and geothermal working substance).

Pressure at the outlet of the turbine is determined by the condition of the saturated state of the organic motive substance. Turbine inlet pressure is determined by the value of the temperature and, at the evaporator outlet, the possible maximum pressure is selected, at which the vapour stream at the turbine outlet will be a single phase. The values of specific electrical power for a variety of halocarbons and their mixtures are shown in Table 1. Thermal properties of the liquid motive substances are taken from [4-6].

At increasing in the temperature of geothermal water, the generation of electric power in the geothermal power plant increases (Fig. 3). The value of the electric power at the temperature of geothermal water of 70 °C for the examined organic motive substance – freon and mixtures thereof – is around 3.2-3.3 kW/(kg/s); at a temperature of 130 °C it's 29,8-31,3 kW/(kg/s). Dependence of the flow on the temperature of the geothermal liquid is shown in Fig. 4.

Results of calculations show that to obtain the maximum specific electrical power, the influence of the pressure values (P_e [kPa]) and steam temperature (t_e [°C]) of the organic motive substance upstream of the turbine, flow rate of the working substance (m [m^3/kW·h]), value of the minimum temperature difference (Δt_{min} [°C]), ambient temperature (t_{ODA} [°C]) and other parameters should be considered.

The impact of the minimum temperature difference is most significant. Thus, reduction of ΔT_{min} from 10-15 K to 5-7 K allows increasing the production of electricity by 20-25 %. Increasing ΔT leads to a lowering of evaporation pressure and temperature, which substantially reduces the efficiency and specific electrical power (N [kW]).

Table 1.

Value of the specific electric power

Heating medium	Evaporation pressure P_e [kPa]	Evaporation temperature t_e [°C]	Temperature of the cooled geothermal water t_H, [°C]	Specific power output N_m [kW/(kg/s)]	Flow rate m [kg/s]	Coefficient of performance COPc
20%R12 + 80% R142b	1452,5	76,27 – 77,59	62,73	29,87	1,096	0,01
10%R12 + 90% R142b	1370,0	76,20 – 76,95	62,97	29,95	1,051	0,01
30%R12 + 70% R142b	1575,0	76,76 – 78,47	62,82	29,87	1,14	0,01
70%R12 + 30% R142b	1925,0	77,61 – 79,23	61,90	30,52	1,35	0,01
80%R12 + 20% R142b	2034,0	78,04 – 79,26	61,73	30,86	1,41	0,01
90%R12 + 10% R142b	2155,0	78,67 – 79,34	61,63	31,29	1,47	0,01

Note: refrigerant mixture in the secondary circuit $t_{T.B.}$ = 130 °C;

Numerical results show that each value of the temperature of geothermal water corresponds to optimum temperature of evaporation of the organic motive substance (Fig. 5). Numerical results show promising use of environmentally friendly refrigerants and their mixtures as organic motive substances for geothermal power stations. At a temperature of 70–130 °C, water geothermal specific electric power to the turbine shaft at installation freon mixtures is 29-31 kW/(kg/s), which is 10-12% higher than for the pure substances cycles 22-24 kW/(kg/s).

It's offered [7] for a geothermal plant with a temperature of thermal water 120 °C to use in the secondary circuit of Freon R13b1 at supercritical parameters. Use of refrigerants R142a, R134b does not allow for expanding the range of thermal water temperature below 150–165 °C. In this work, a mixture of refrigerants (R13b1 + R142b), (R13b1 + R13) was studied. The results of the calculation of parameters beyond the critical cycle for a mixture of Freons (80%R13b1 + 20%R142b), thermal water temperature –130 °C are shown in Table.2.

In the thermodynamic analysis of the system conversion of geothermal energy into electrical energy, the following assumptions are taken:

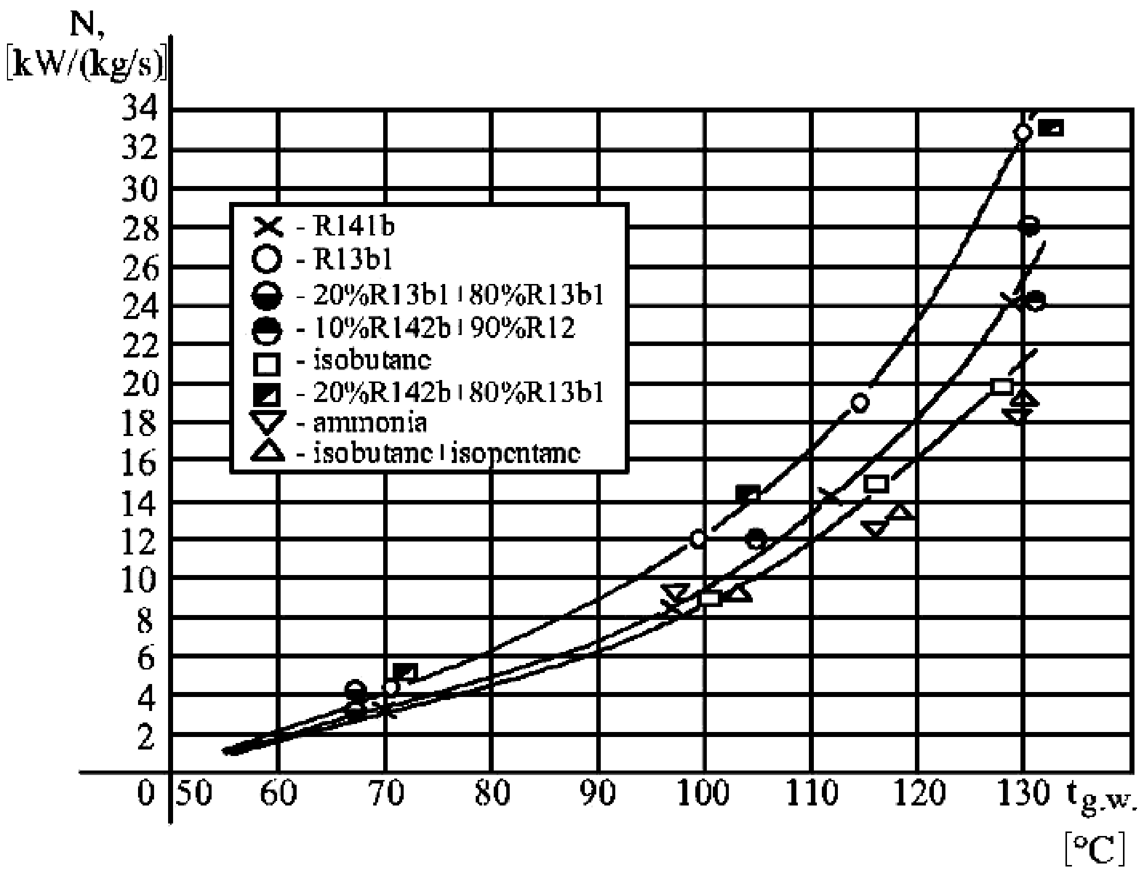

Fig. 3. Dependence of specific electric power of geothermal power station on the temperature of the geothermal water

- all the processes occurring in the system are reversible;
- state of the fluid coming out (coming in) from the system is in thermodynamic equilibrium with the environment.

Equation of the second law of thermodynamics for a geothermal circulation system is:

$$-\sum_{i=1}^{n} m_i s_i - \int_{\tau_1}^{\tau_2} \frac{1}{T}\frac{dQ}{d\tau} d\tau = 0, \tag{9}$$

where s_i – entropy in i-th point, kJ/K; τ – time, s; τ_1 – time of the process start, s; τ_2 – time of the process finish, s; Q – the heat power, J. The integral in (9) the change in entropy in the system is equal to the production of entropy due to irreversibility.

Equation of the first law of thermodynamics after disregarding the change in kinetic and potential energy of the organic motive substance is:

$$Q - W = m\,(h_2 - h_1), \tag{10}$$

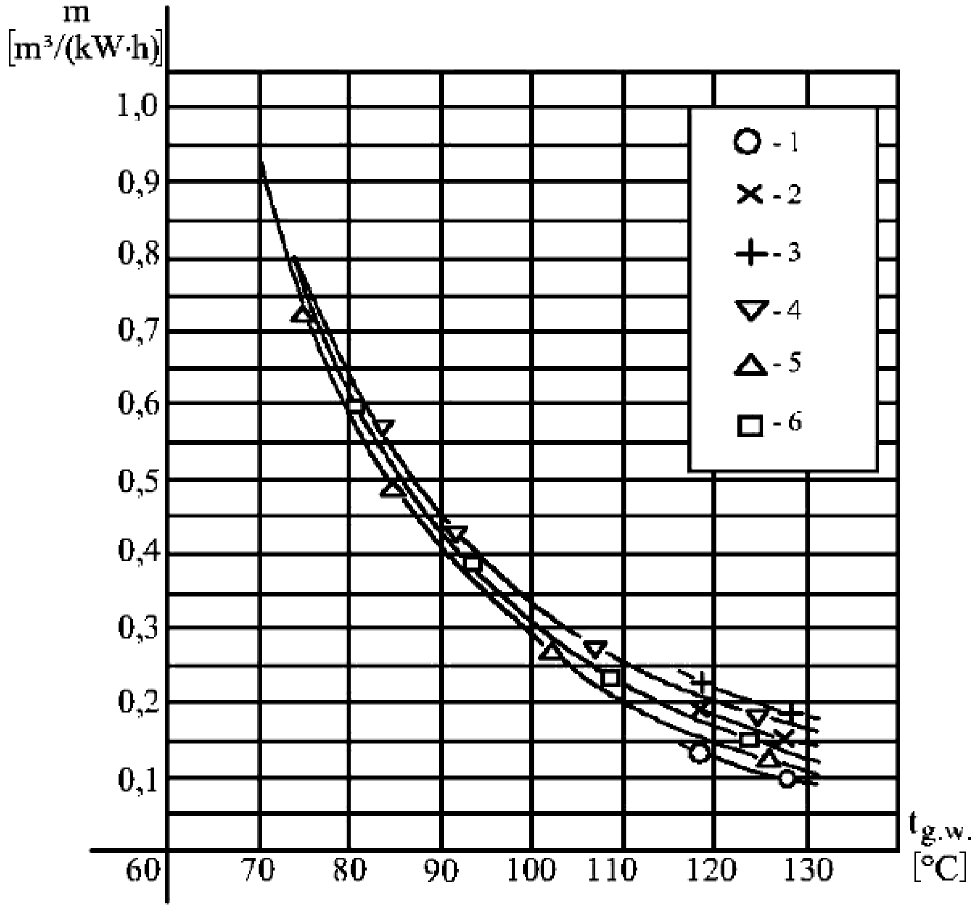

Fig. 4. Dependence of the flow of geothermal water temperature for different organic motive substances: 1 – isobutane (t_e = 7 °C, Δt_{min}=10 K), 2 – isobutane (t_e = 30 °C, Δt_{min}=10 K), 3 – isobutane (t_e = 30 °C, Δt_{min}=20 K), 4 – R142b (t_e = 25 °C, Δt_{min} = 10 K); 5 – R13b1 (t_e = 25 °C, Δt_{min} = 10 K); 6 – 20% R142b + 80% R13b1 (t_e = 25 0C, Δt_{min}=10 K).

where W – the work performed, J.

Since the system interacts with the environment only through the transfer of heat, equations (12) and (13) have the form:

$$-m\cdot(s_1 - s_2) - (Q_0/T_0) = 0, \quad (11)$$

$$Q_o - W = m\,(h_2 - h_1), \quad (12)$$

$$W = m\,[h_1 - h_2 - T_o\,(s_1 - s_2)]. \quad (13)$$

where Q_0 – the heat transmitted to the system or from it at ambient temperature; T_0 – the ambient temperature for which the exergy and the maximum useful work are determined.

Assuming that the final state is identical to the "marginal" status, we obtain an expression for the calculation of the maximum energy (exergy).

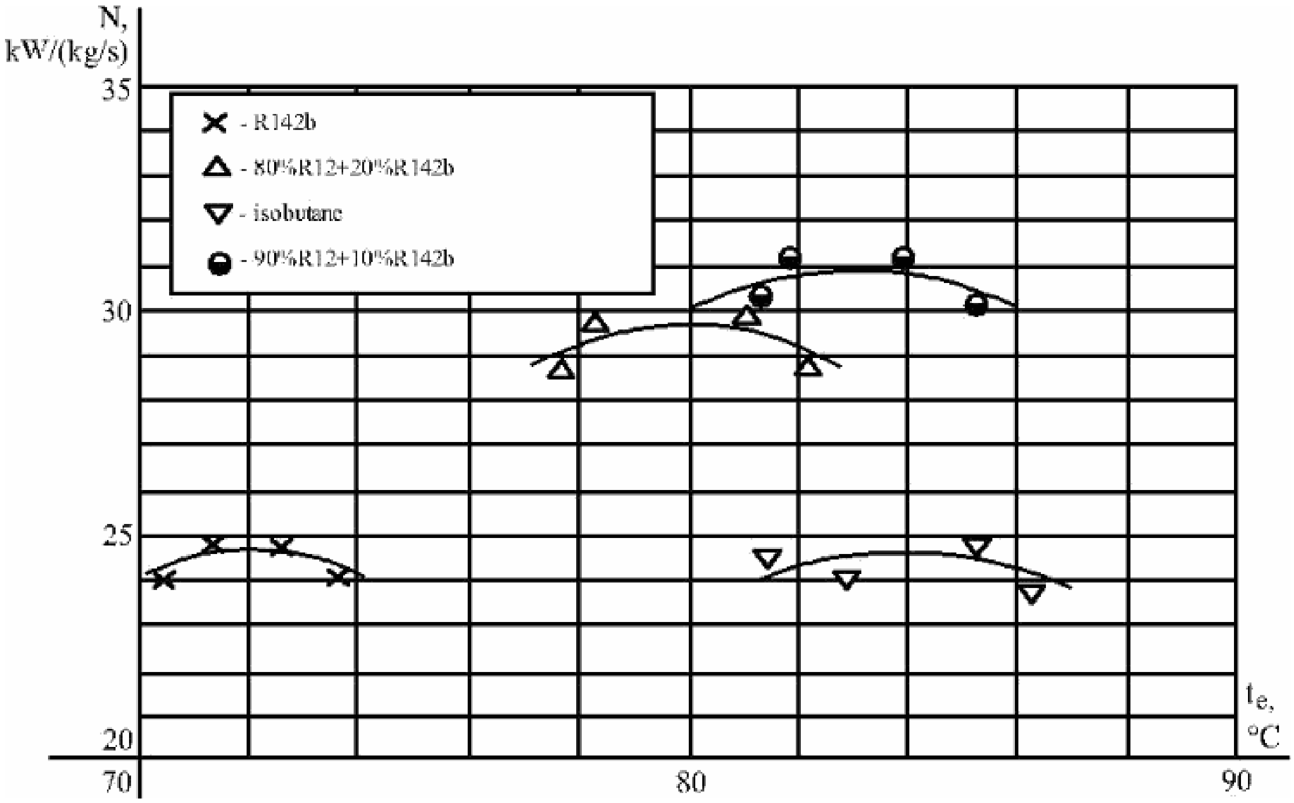

Fig. 5. Dependence of specific electric power on evaporation temperature

Table 2. Parameters of supercritical cycle (R13 + R13b1)

Proportion of mixture	*N* [kW/(kg/s)]	*m*, [kg/s]	COP [%]
80%R13+20%R13b1	17,00	3,02	4,6
50%R13+50%R13b1	22,57	3,13	6,04
20%R13+80%R13b1	28,48	3,30	7,58
10%R13+90%R13b1	30,57	3,36	8,14

We define Q_0, W, in equation and substituting in (13), and obtain

$$W_m = m\ [h_1 - h_0 - T_o\ (s_1 - s_0)]. \quad (14)$$

Expression in parentheses defines the value of the specific exergy.

With the increase in the temperature of geothermal water to 130 °C, thermodynamic efficiency characteristics vary.

Coefficient of utilization cycle of geothermal power station at a temperature of geothermal water of 70 °C is about 11.50 % at 130 °C. The energetic efficiency (gross) of the turbine is 28,50-54,88 %.

Most effective working substances for cycles of geothermal power plants at a temperature of geothermal fluid of 130 °C are R134a, R22, R143a, R218, R13b1, and the mixture (80% R13b1 + 20% R142b).

Conclusions. Numerical studies of binary thermodynamic efficiency of geothermal power plants have shown that in cycles with Freons R13b1, R22, and R134a, an electric power output of 34.0-43.3 kW/(kg·s) is provided at a temperature of the geothermal liquid of 130 °C. There is a significant influence of the steam pressure and temperature, the flow of the organic motive substance, and the minimum value of the temperature difference in heat exchange equipment (evaporator, condenser) on the effectiveness. Use of mixtures of halocarbons provides increased production of electric power up to 10-12 % and above. Analysis of the thermodynamic cycle efficiency of the equipment in the geothermal power plant shows that at the geothermal liquid temperature of 130 °C, the thermal efficiency is from 7.58 to 10.96%, and the coefficient of cycle utilization is from 28.50 to 54.88%.

Thus, in consideration of the cycles thermal fluid temperature at the turbine outlet is from 63,2 to 86,2 °C for R22 and R134a, from 28,1 °C to 91,1 °C for R318, which indicates the possibility of an increase in the efficiency provided by a deeper drop in temperature of the working substance in the turbine.

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УДК 669.2

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https://doi.org/10.32347/2409-2606.2025.55.115-127

ТЕРМОДИНАМІЧНИЙ АНАЛІЗ ЕФЕКТИВНОСТІ ТЕПЛОВОЇ СХЕМИ ГЕОТЕРМАЛЬНОЇ ЕЛЕКТРОСТАНЦІЇ

Анотація. *Вивчалися бінарні цикли чистих робочих речовин R144a, R22, R143a, R218, R13b1 та сумішей (R13b1+ R142b) (R13+ R13b1), (R12+ R142b), при температурах 70 °C та 130 °C, при різноманітній температурі навколишнього середовища (15, 20, 25°C), мінімальній температурній різниці між робочими рідинами та геотермальною робочою сумішшю (Δt = 5, 10, 15K). Наведено результати чисельних досліджень ефективності теплової схеми геотермальної електростанції. Проводився обрахунок потужності, що вироблялась енергетичним устаткуванням, та утилізації теплоти геотермальної рідини. Показано, що потужність, яка виробляється за температури 70 °C становить 3,2-3,9 кВт/(кг/с), а за температури 130 °C маємо 29,8-31,9 кВт/(кг/с). Висока ефективність бінарної геотермальної установки з робочою рідиною ізобутан забезпечує зниження масової витрати геотермальної рідини до 0,1-0,2 м^3/(кВт·год) за температури 130 °C. Електрична потужність, яка виробляється, залежить від температури геотермальної рідини. При температурі води 70-130 °C геотермальна питома* *потужність турбіни при використанні суміші холодоагентів повинна становити 24-31 кВт/(кг/с), що на 10-12 % вище, ніж для чистого робочого циклу рідини – 22-24 кВт/(кг/с). Показано, що кожна робоча рідина ефективна у визначеному температурному інтервалі. Наприклад, холодоагент R13b1 ефективний при температурі геотермальної рідини 120 °С, а R142a та R134b ефективні при температурі 150-165°С. Використання різноманітних робочих тіл забезпечує різноманітні коефіцієнти використання циклів геотермальними електростанціями. При температурі геотермальної рідини 70 °С маємо близько 11,5 %, при 130°С, відповідно, від 28,5 до 54,88%. Показано, що в бінарних енергетичних установках ефективними при температурі геотермальної рідини на рівні 130 °С є холодоагенти R134a, R143a, R218, R113b1 та суміші (80% R13b1+20% R142b).*

Ключові слова: *геотермальна енергія, геотермальна електростанція, холодоагент, бінарний цикл.*

Received/Надійшла до редакції 06.10.2025
Reviewed/Рецензована 18.12.2025
Accepted/Прийнята 20.12.2025