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Rational parameters of a hybrid geothermal power plant based on Flash/ORC cycles

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Abstract: The numerical simulation results of the thermal scheme of a power plant related to steam and organic cycles are presented. The rational parameters of the cycles of the geothermal energy conversion unit have been determined. In addition, various organic working fluids are studied. The rational parameters of the thermodynamic cycles at a geothermal fluid temperature of 250°C have also been defined.

Keywords: geothermal energy, power plant, thermodynamic cycles, numerical simulation

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Introduction

Currently, renewable energy sources (RES) are increasingly being used, with geothermal energy the most widely used for electricity production (Redko et al., 2019). ORC technology is implemented in power plants, however, its use is limited by the steam temperature of organic working fluids (OWF), which is about 200-220°C. At a higher geothermal fluid temperature, it is possible to use butane, pentane, hexane and other organic heat-carriers (DiPippo, 2015). Their main disadvantage is that they are fire and explosion hazards. Therefore, at present, research is being carried out with aim of creating a rational technological scheme for a geothermal power plant, in which it is possible to use industrial steam turbines and steam turbine plants that use OWF. Combined technological schemes are used in metallurgical and cement plants (Machi & Astolfi, 2017). There are two groups of geothermal power plants, namely steam and binary power cycles. The dual flash steam plant is preferred over the single flash steam power plant depending on the conditions of the resource. Using two separators leads to the use of a two-stage steam turbine. Dual flash power plants are able to produce up to 25% more power than single flash plants.

The Polish Geological Institute – National Research Institute, has designated many locations in Poland with favourable conditions for the construction of geothermal heat plants (Fig. 1) (Gulewicz, 2020). The geothermal conditions in Poland indicate the rational use of ORC for energy production in hybrid geothermal power plants (Mróz & Grabowska, 2019).

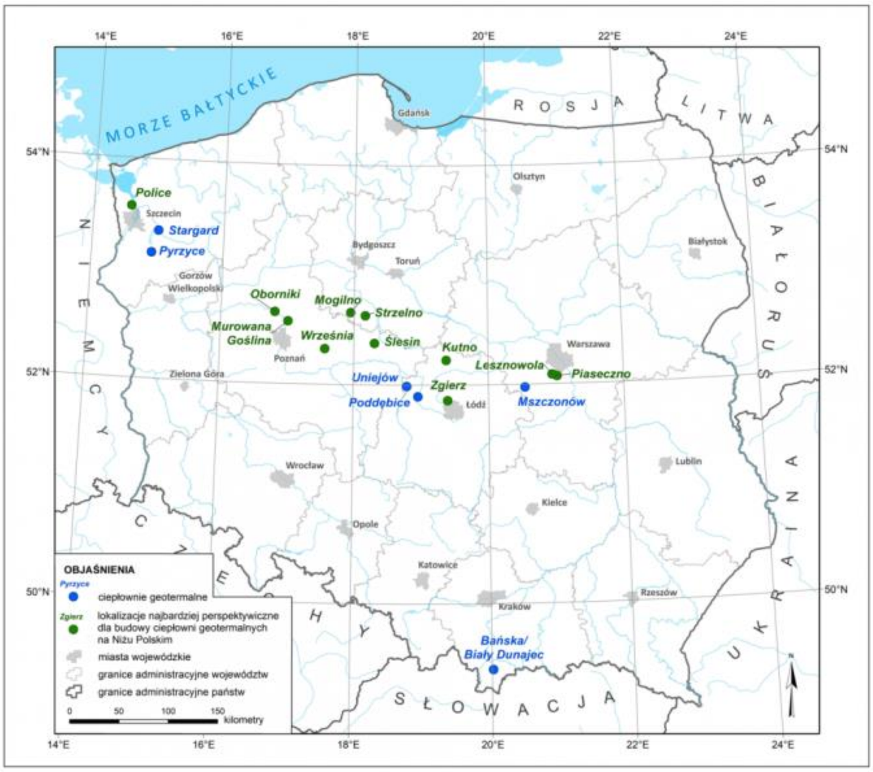

Fig. 1. The most prospective locations for the construction of geothermal heating plants (green) and the locations of the existing geothermal heating plants (blue) (Gulewicz, 2020)

The potential of geothermal energy in Ukraine is equivalent to 12 million tons of conventional fuel or 10 billion m^3 of natural gas. By 2030, it is planned to create geothermal power plants with a total capacity of 2,160 MW and an electrical capacity of 400 MW. Perspective geothermal regions of Ukraine include the following: the Carpathian geothermal region, the Crimea, and the Dnieper-Donetsk cavity (Eastern region of Ukraine). Nowadays, the industrial development of geothermal sources in Ukraine is not being carried out, but a geothermal installation with a capacity of 1 MW in the Crimea, and a geothermal installation in Transcarpathia, also with a capacity of 1 MW, are in pilot operation (Kudria).

The aim of this work is to study the influence of the thermodynamic properties of the working bodies of a hybrid power plant on the generated electric power.

1. Schematic thermal diagram of a hybrid power plant

Article (Bruscoli et al., 2015) studies the environmental sustainability of geothermal energy production. The efficiency of energy conversion at a hybrid (steam/ORC) geothermal power plant is analyzed using the example of a geothermal power plant located in the geothermal zone of Monte Amiata, Italy, Tuscany with an additional ORC cycle and a n-pentane heat-carrier. The cycle temperature is 150°C. Various thermal schemes with ORC cycles and various working fluids (n – hexane, R123, R245fa, isopentane, n – pentane, n – butane) are studied. The generated power is about 2300 kW in the ORC cycle with the n-hexane working fluid.

A comparison of the thermodynamic efficiency of various technologies for converting geothermal energy is given in (Taghaddosi, 2005). It is shown that the energetic efficiency of the binary – flash evaporator technology (Otaka pilot plant) reaches 53.9%.

The parameters of geothermal flash-binary power plants with different cycles (basic ORC, regenerative ORC and ORC with internal heat exchanger) are studied in (Kaplam, 2007). The effect of flashing pressure, working fluid selection and extraction pressure is also studied. It is shown that the optimum flashing pressure for flash-binary power plants using basic ORC is 763.9 and 775.7 kPa. R123 is used as a working fluid.

Papers (Gong et al., 2010; El Haj Assad et al., 2017; Yazdi, 2017, Tomasini--Montenegro et al., 2017) present data on the action of Flash/ORC GPP with the following parameters: steam pressure 1.5 bar; steam temperature 250ºC; Wf at ORC is set to be C_5H_{12} n-pentane.

The technological scheme of the hybrid geothermal power plant is shown in Figure 2 (DiPippo, 2015). The installation contains well 1 for the selection of geothermal fluid, a separator and well 2 for the re-injection of geothermal fluid into the formation. The installation contains the 1st circuit with the organic working fluid, connected to the steam condenser and the 2nd circuit with ORT, connected to the liquid heat exchanger after the separator. 1st and 2nd circuits include an ORT steam turbine as well as an electric generator, a condenser and a pump. The temperature of the geothermal fluid is assumed to be 250°C, being in the state of a saturated liquid (state 1). In the process of throttling (1-2), wet steam is formed with a degree of dryness X. The wet steam enters a separator where saturated liquid and steam are separated. The amount of steam depends on the degree of dryness in state 2. Saturated steam is supplied to the turbine, where it is expanded into the process (4-5). Saturated liquid with high temperature enters the 1st ORC loop (a-b-c-d-e-f), where it gives off heat to the steam of the organic working fluid. After condensation, water vapor gives off heat in the 2nd ORC circuit (u-v-w-x-y). Thus, deep utilization and transformation of geothermal fluid heat takes place. The circuit is shown in Figure 2.

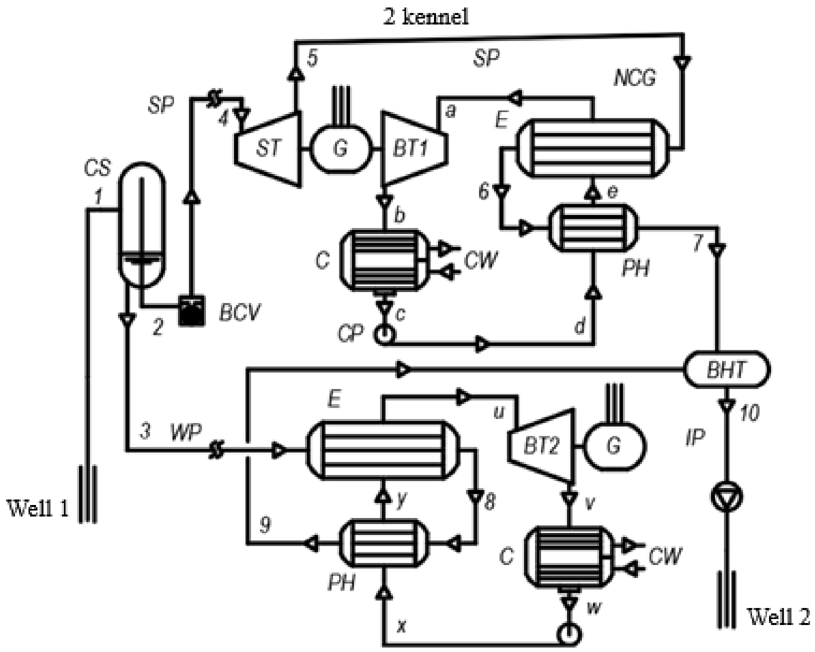

Fig. 2. Schematic thermal diagram of a hybrid power plant (*own study based on DiPippo, 2015*)

Power output of the steam turbine:

$$\dot{W}_{ST} = \dot{m}_4(h_4 - h_5) \quad (1)$$

Next, we can assess the upper binary cycle, loop 1. The turbine power is found from

$$\dot{W}_{BT1} = \dot{m}_{C_5}(h_a - h_b) \quad (2)$$

and the feed pump power is found from

$$\dot{W}_{CP1} = \dot{m}_{C_5}(h_e - h_d) \quad (3)$$

Thus, the second objective may be determined:

1. Net power output of the upper binary cycle

$$\dot{W}_{B1,net} = \dot{W}_{BT1} - \dot{W}_{CP1} \quad (4)$$

Next, we assess the lower binary cycle, loop 2, in the same fashion:

$$\dot{m}_{C_5} = \dot{m}_b(1 - x_2)\left[\frac{h_3 - h_9}{h_u - h_x}\right] \tag{5}$$

Then the turbine and pump power follow directly:

$$\dot{W}_{BT2} = \dot{m}_{C_5}(h_u - h_v) \tag{6}$$

$$\dot{W}_{CP2} = \dot{m}_{C_5}(h_x - h_w) \tag{7}$$

2. Net power output of the lower binary cycle

$$\dot{W}_{B2,net} = \dot{W}_{BT2} - \dot{W}_{CP2} \tag{8}$$

The cycle thermal efficiencies are the ratio of the net power output to the thermal power input for each loop. The two heat transfer terms are found from:

$$\dot{Q}_{IN1} = \dot{m}_{C_5}(h_a - h_e) \tag{9}$$

$$\dot{Q}_{IN2} = \dot{m}_{C_5}(h_u - h_x) \tag{10}$$

We can now find our fourth objective:

3. Cycle thermal efficiency for both loops

$$\eta_{B1,th} = \frac{\dot{W}_{B1}}{\dot{Q}_{IN1}} \tag{11}$$

$$\eta_{B2,th} = \frac{\dot{W}_{B2}}{\dot{Q}_{IN2}} \tag{12}$$

The last objective requires us to find the exergy of the original reservoir fluid, taken to be a saturated liquid at the reservoir temperature. The specific exergy is

$$e_1 = h_1 - h_0 - T_0[(s_1 - s_0)] \tag{13}$$

and the rate at which exergy is produced from the reservoir is

$$\dot{E}_1 = \dot{m}_1 e_1 \tag{14}$$

The net power of the whole plant (ignoring parasitic loads such as cooling tower fans and pumps) is

$$\dot{W}_{plant} = \dot{W}_{ST} + \dot{W}_{B1,net} + \dot{W}_{B2,net} \tag{15}$$

Thus, we find our last objective:

4. Overall plant utilization efficiency:

$$\eta_u = \frac{\dot{W}_{plant}}{\dot{E}_1}$$

Results of the numerical calculation of the parameters of a hybrid power plant at a water vapor temperature of 205°C (Table 1)

Initial data:
- efficiency of a steam turbine is 0.80;
- efficiency of n-pentane turbines is 0.85;
- efficiency of pumps is 0.75.

Ambient temperature is 25°C.
Temperature difference between under recovery and at the pinch point is 5 K.
The power of the steam turbine is 39.54 kW.
The power of n-pentane turbines is 81.88 and 32.91 kW.
The power of n-pentane pumps is 2.822 and 0.6868 kW.

Table 1. Results of the numerical calculation of the parameters of a hybrid power plant at a water vapor temperature of 205°C (*own study*)

No	P, kPa	t, °C	x	s, kJ/(kg·K)	i, kJ/kg	G, kg/s
1	3975.96	250.00	0.0000	5.50086	14867.135	1.0000
2	1722.75	205.00	0.1147	5.52878	–14867.135	1.0000
3	1722.75	205,00	0.0000	5.05805	15092.215	0.8853
4	1722.75	205.00	1.0000	9.16149	13130.152	0.1147
5	150.00	111.18	0.9068	9.38570	13474.834	0.1147
6	150.00	111.18	0.2812	5.74526	14873.999	0.1147
7	150.00	35.343	0.0000	3.21490	15811.497	0.1147
8	1722.75	151.17	0.0000	4.52362	15333.303	0.8853
9	1722.75	70.357	0.0000	3.64813	15668.506	0.8853
10	150.00	66.655	0.0000	3.60571	15684.910	1.0000
a	683.00	106.18	1.0000	2.41905	1899.9855	0.5483
b	104.70	66.571	1.0000	2.45049	1960.0125	0.5483
c	104.70	30.000	0.0000	1.07148	2390.1392	0.5483
d	683.00	30.344	0.0000	1.07262	2388.8866	0.5483
e	683.00	106.15	0.0000	1.64725	2192.7333	0.5483
u	1505.00	146.17	1.0000	2.50182	1838.8183	0.9305
v	104.70	83.863	1.0000	2.54581	1926.8091	0.9305
w	104.70	30.000	0.0000	1.07148	2390.1392	0.9305
x	1505.00	30.830	0.0000	1.07424	2387.1061	0.9305
y	1505.00	146.17	0.0000	1.95482	2068.1914	0.9305

In Table 1 No 1-10 is water vapor; a, b is the organic cycle and c-y is the second organic cycle.

Conclusion

The results of the numerical study show that a hybrid geothermal power plant provides the generation of specific electric power in a steam turbine from 39.5 to 44.5 kW/kg and power in an n-pentane ORC complex from 93.7 kW/kg up to 114.8 kW/kg when the temperature of water vapor changes from 185 to 205°C. The geothermal fluid temperature is 250°C. The thermodynamic efficiency of the installation is 0.58-0.63%. Replacing the OWF with R152a and R600a/r141b increases the generated power up to 149.5 kW/kg the total generated power being 175.4 kW/kg.

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