Improving the performance of geothermal power plant by substituting water steam power plant for the binary power plant

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ABSTRACT

The paper presents a mathematical model of a power plant two variants: a water steam power plant using fossil fuel and geothermal energy and a binary power plant with water and organic substance as working media, powered with fossil fuel and co-powered with geothermal energy. Power and efficiency calculations for a binary power plant have been performed, and the results have been compared with power and efficiency values obtained for a conventional power plant with water as working medium. The calculations have been made with an assumption of a constant value of heat flux from fossil fuel and maintaining comparable working conditions of the power plan in all the variants considered.

1. INTRODUCTION

The starting point for assessment of the effectiveness of operation of different power plant design is a single component superheated cycle power plant, where water serves as circulation fluid. Such power plant will be replaced with a binary power plant operating in the same range of high and low reservoir temperatures. Heat transfer in the binary power plant from the high temperature reservoir to the low temperature reservoir takes place in the heat exchanger of condenser/evaporator type.

In the paper presented and discussed will be schematics of operation of both power plants operating in accordance to the Clausius-Rankine cycle. Presented also will be algorithms of calculation encompassing such quantities as efficiency and powers of respective cycles. Calculations will be carried out for selected organic fluids of the low-pressure cycle of a two stage cycle. The results of calculations will be presented in the form of relevant distributions enabling carrying out of a comparative assessment of a binary cycle and a single fluid cycle, which will enable formulation of arising final conclusions. If you use equations, define all symbols, either after the equation, or in a Nomenclature section at the end of the paper.

2. CALCULATION METHODOLOGY FOR PARTICULAR POWER PLANT TYPES

Presented below are the relations used for calculations of particular steam power plant variants, as well as the assumptions and calculation procedure.

2.1. Steam power plant variant using fossil fuel and geothermal energy

In the first stage of the analysis, calculations have been carried out for a steam-water power plant presented in Figure 1, powered from two sources:

- superheating, evaporation and heating of working medium in higher temperature range – the source of heat is fossil fuel, and

- heating of working medium in lower temperature range with energy from geothermal water stream.

The power plant works according to thermodynamically process Rankine cycle, what is presented at Figure 2.

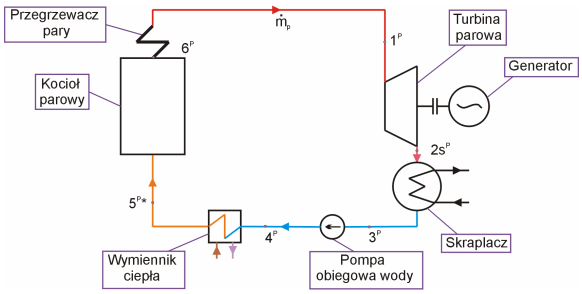

Fig. 1. Scheme of a steam water power plant powered with fossil fuel and geothermal energy

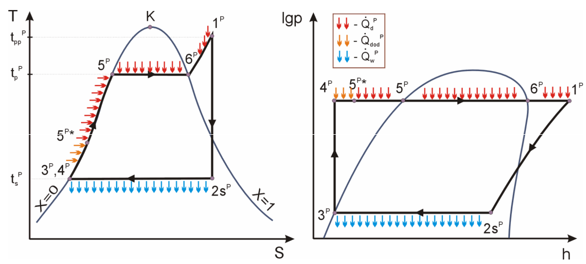

Fig. 2. Cycle of thermodynamical processes of steam water power plant

In the calculations for variant primary of the power plant the following relations have been used.

Heat flux supplied to the cycle from the boiler and geothermal heat exchanger and used for heating, evaporation and superheating of the working medium has been calculated according to the following relation:

$$\dot{Q}_d^P = \dot{Q}_{geo}^P + \dot{Q}_{dk}^P \tag{1}$$

where:
- heat flux transferred to the working medium (water) in geothermal heat exchanger:

$$\dot{Q}_{geo}^P = \dot{m}_p \cdot \left(h_5^{P*} - h_4^P\right) \tag{2}$$

- heat flux supplied to the working medium from the boiler (water, steam):

$$\dot{Q}_{dk}^{P} = \dot{m}_{p} \cdot \left(h_{1}^{P} - h_{5}^{P*}\right) \tag{3}$$

Heat flux carried away from the cycle in the steam condenser:

$$\dot{Q}_{w}^{P} = \dot{m}_{p} \cdot \left(h_{2s}^{P} - h_{3}^{P}\right) \tag{4}$$

In the calculations of the power of Clausius-Rankine cycle can be described relation for isentropic expansion process in the turbine:

$$N_{C-R}^{P} = \dot{m}_{p} \cdot \left(h_{1}^{P} - h_{2s}^{P}\right) \tag{5}$$

or relation for energy balance equation:

$$\dot{Q}_{d}^{P} = \dot{Q}_{geo}^{P} + \dot{Q}_{dk}^{P} = N_{C-R}^{P} + \dot{Q}_{w}^{P} \tag{6}$$

from where after transformation:

$$N_{C-R}^{P} = \dot{Q}_{d}^{P} - \dot{Q}_{w}^{P} \tag{7}$$

Efficiency of the Clausiusa-Rankinea cycle calculated from the following relation:

$$h_{C-R}^{P} = \frac{N_{C-R}^{P}}{\dot{Q}_{d}^{P}} = 1 - \frac{\dot{Q}_{w}^{P}}{\dot{Q}_{d}^{P}} \tag{8}$$

Heat flux used for heating of working medium in the enthalpy range from h_5^{P*} to h_4, calculated from the formula:

$$\dot{Q}_{geo}^{p*} = \dot{m}_{p}\left(h_{5}^{P*} - h_{4}^{P}\right) = + \dot{m}_{geo} c_{pgeo}\left(T_{geo1} - T_{geo2}\right) \tag{9}$$

where h_5^{P*} depends on T_{geo1}.

The calculations for primary cycle were based on the assumption that the superheating temperature of steam was 370°C at 34 bar pressure, corresponding to a pressure of 0.04 bar and steam humidity of x = 0,86 at the end of isentropic expansion in the turbine. The working medium flow was assumed at $\dot{m}_p = 1 kg/s$.

The calculations have been made for the assumed value of geothermal water temperature T_{geo1} = 40 - 100°C. The geothermal heat flux and geothermal water flow required to supply the pre-heater of the power plant can be calculated from formula (9).

2.2. Binary power plant variant

Another, second variant of the power plant, marked as binary plant, is presented in Figure 3. This power plant consists of an upper cycle, where water is used as working medium, and a lower cycle, where the working medium is one of a few organic substances (R227ea, butane, isobutene, R236ea, R236fa, R245ca, R245fa, RC318).

The power plant works according to thermodynamically processes Rankine cycle, what is presented at Figure 4.

It has to be emphasized that water is a so-called wet medium, which, depending on the assumptions regarding the power plant cycle, should be superheated to a smaller or larger degree before being sent to the turbine, whereas the selected organic media belong to the group of dry media, for which the superheating process is not necessary, often even not advisable. This allows to avoid additional energy input for superheating of working medium. The upper cycle is powered entirely with energy from burning the fuel in the boiler, whereas the lower cycle is partially powered with the energy from the boiler and co-powered with energy from geothermal water.

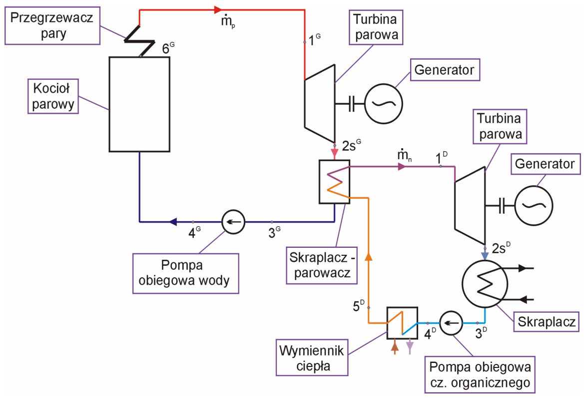

Fig. 3. Scheme of a binary power plant co-powered with fossil fuel and geothermal energy

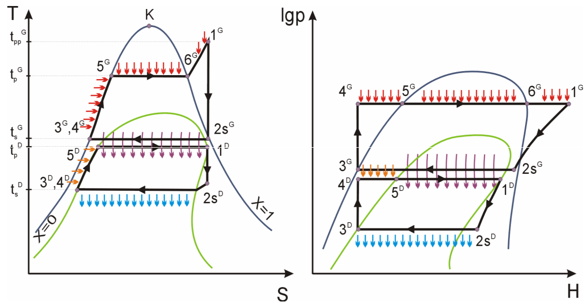

Fig. 4. Cycles of thermodynamical processes of a primary power plant

2.2.1. Calculation methodology for upper cycle of binary plant

The mathematical model calculations of the binary power plant is described by the following relations.

Heat flux supplied to the upper cycle from the boiler used for heating, evaporation and superheating of the working medium calculated from the following relation:

$$\dot{Q}_{d}^{G} = \dot{m}_{p}^{G}\left(h_{1}^{G} - h_{4}^{G}\right) \tag{10}$$

Heat flux carried away from the cycle for condenser-evaporator type of heat exchanger:

$$\dot{Q}_{w}^{G} = \dot{Q}_{s-p} = \dot{m}_{p}^{G}\left(h_{2s}^{G} - h_{3}^{G}\right) \tag{11}$$

For calculations of the power of C-R upper cycle can be used relation for isentropic expansion process in the turbine:

$$N_{C-R}^{G} = \dot{m}_{p}^{G}\left(h_{1}^{G} - h_{2s}^{G}\right) \tag{12}$$

or transformed relation of energy balance equation:

$$N_{C-R}^{G} = \dot{Q}_{d}^{G} - Q_{w}^{G} \tag{13}$$

Efficiency of the Clausiusa-Rankinea upper cycle calculated from the following relation:

$$h_{C-R}^{G} = \frac{N_{C-R}^{G}}{\dot{Q}_d^G} = 1 - \frac{\dot{Q}_w^G}{\dot{Q}_d^G} \tag{14}$$

The element linking the upper and lower cycle (according to Fig. 3 and Fig. 4) is a heat exchanger (evaporator-condenser), whose energy balance can be expressed as follows:

$$\dot{Q}_{s-p} = \dot{m}_p^G \left(h_{2s}^G - h_3^G\right) = \dot{m}_n^D \cdot \left(h_1^D - h_5^D\right) \tag{15}$$

Using the balance equation for this exchanger can determine the working medium flow in the upper cycle as a function of the flow of medium in the primary cycle.

$$\dot{m}_n^D = \dot{m}_p^G \frac{h_{2s}^G - h_3^G}{h_1^D - h_5^D} \tag{16}$$

2.2.2. Calculation methodology for lower cycle of binary plant

Expressed below are the mathematical relations for the lower cycle, in which organic substance is the working medium.

The total heat flux supplied to the lower cycle from evaporator-condenser heat exchanger and geothermal heat exchanger for heating, evaporation and superheating of the working medium (organic medium) have been calculated from the following relation:

$$\begin{aligned} \dot{Q}_d^D &= \dot{Q}_{s-p} + \dot{Q}_{geo}^D = \\ &= \dot{m}_n^D \left(h_5^D - h_4^D\right) + \dot{m}_n^D \left(h_1^D - h_5^D\right) \end{aligned} \tag{17}$$

Heat flux carried away from the cycle in the condenser:

$$\dot{Q}_w^D = \dot{m}_n^D \left(h_{2s}^D - h_3^D\right) \tag{18}$$

Analogical, for calculations of the power of C-R lower cycle can be used relation for expansion process in the turbine:

$$N_{C-R}^D = \dot{m}_n^D \left(h_1^D - h_{2s}^D\right) \tag{19}$$

or transformed of energy balance equation:

$$N_{C-R}^D = \dot{Q}_d^D - Q_w^D \tag{20}$$

Efficiency of the Clausiusa-Rankinea lower cycle calculated from following relation:

$$h_{C-R}^{D} = \frac{N_{C-R}^{D}}{\dot{Q}_d^D} = 1 - \frac{\dot{Q}_w^D}{\dot{Q}_d^D} \tag{21}$$

2.2.3. Calculation methodology for binary plant

The total heat flux transferred to the binary plant (binary cycles) is a sum of heat flux transferred to upper cycle and transferred in geothermal heat exchange in lower cycle:

$$\dot{Q}_d^B = \dot{Q}_d^G + \dot{Q}_d^D \tag{22}$$

It can be written:

$$\dot{Q}_d^B = \dot{m}_p^G \left(h_1^G - h_4^G\right) + \dot{m}_n^D \left(h_5^D - h_4^D\right) \tag{23}$$

Heat flux carried away from the binary cycle is equal to the energy flux carried away from the primary cycle:

$$\dot{Q}_w^B = \dot{Q}_w^D = \dot{m}_n^D \left(h_{2s}^D - h_3^D\right) \tag{24}$$

The total power of the binary plant was calculated from the energy balance as a sum of the power of upper and lower cycle:

$$N_{C-R}^B = N_{C-R}^G + N_{C-R}^D \tag{25}$$

The binary plant efficiency was calculated from relation:

$$h_{C-R}^{B} = \frac{N_{C-R}^{B}}{\dot{Q}_d^B} = \frac{N_{C-R}^G + N_{C-R}^D}{\dot{Q}_d^G + \dot{Q}_d^D} \tag{26}$$

The calculations for the upper cycle of a binary power plant were carried out and based on the assumption that the condensation of steam takes place at the temperature $T_{2s}^G = T_3^G$ = 40 - 80 °C. The expansion process in the turbine takes place from the same value of superheated steam temperature as in the primary cycle, and to the same value of steam humidity at the turbine outlet.

The lower cycle operates in the following temperature range: upper heat source with a temperature of $T_5^D = T_1^D = T_{2s}^G$ - ?T, being the condensing steam, and the condensation point of organic medium T_s^D = 29°C, which is the water condensation point in the primary cycle. The temperature difference between the condensing steam and the evaporating organic medium was assumed at ?T = 3K. The assumptions for geothermal water temperatures were identical as for variant B, i.e. T_{geo1} = 40 - 100°C.

3. Results of calculations

The calculations were carried out for the two variants of the power plant. The exemplary results of calculations are presented in Table 1. These results were taken from the work [5].

In the paper presented have been The results of calculations two analyzed variants of geothermal power plants have been presented on Figures 5 - 8.

On Figure 5 presented is influence of evaporation temperature of medium in lower cycle on power of binary power plant (for isobutan).

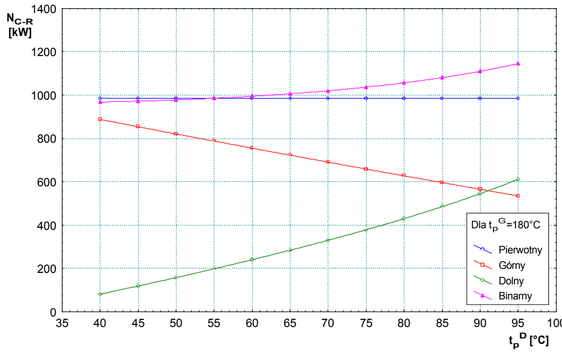

Fig. 5. Influence of evaporation temperature of medium in lower cycle on power of binary power plant (for isobutan)

On Figure 6 presented is influence of type of medium in lower cycle on power of binary power plant. On Figure 7 presented is influence of evaporation temperature of medium and type of medium in lower cycle on efficiency of binary power plant. On Figure 8 presented is influence of medium type and evaporation temperature of medium on geothermal heat flux.

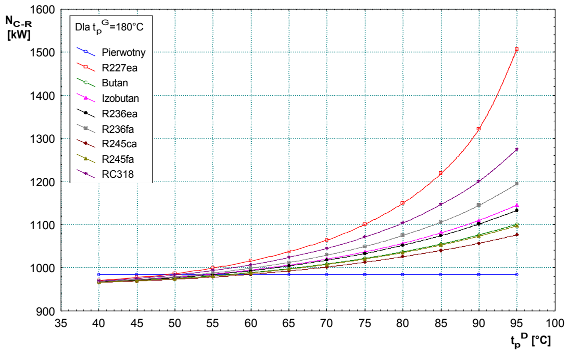

Fig. 6. Influence of evaporation temperature of medium and type of medium in lower cycle on power of binary power plant

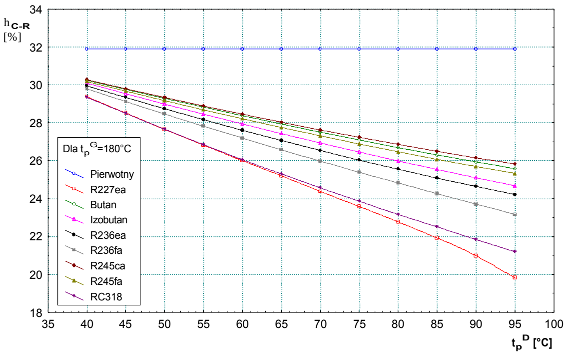

Fig. 7. Influence of evaporation temperature of medium and type of medium in lower cycle on efficiency of binary power plant

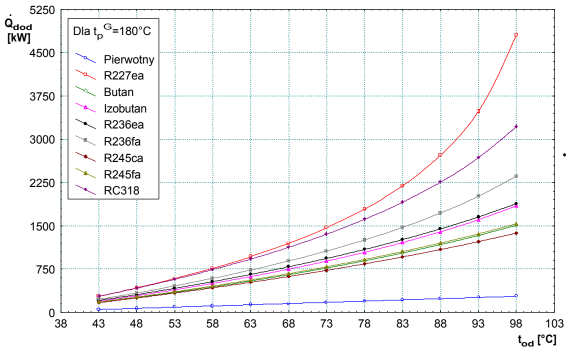

Fig. 8. Influence of medium type and evaporation temperature of medium on geothermal heat flux

Figures present the turbine power of particular power plant variants as a function of evaporation temperature (organic medium). The analysis of this chart shows that the additional supply of the power plant with a geothermal water stream with specified temperature allows to obtain higher power values of the power plant, however only after the introduction of binary cycle with low-boiling medium in lower cycle has it resulted in significant improvement of the effectiveness of the power plant. This results primarily from the fact that organic media have much lower values of evaporation enthalpy compared to water, which affects the amount of circulating medium in the cycle at the assumed constant value of supplied heat flux. The analysis shows that the use of the binary solution with low-boiling medium in the lower cycle makes it possible to make better use of the low-enthalpy geothermal energy compared to a classical power plant with water as a working medium. This is related to the fact that the heating enthalpy of an organic medium is close and sometimes higher than the evaporation enthalpy of that medium (depending on the type of medium and proximity to the critical point).

3. Conclusions

The paper has presented a power plant model with water organic fluid as working media, powered by fossil fuel energy and co-powered with geothermal energy. Power and efficiency calculations have been performed, and the results for binary power plant have been compared with power and efficiency values obtained for a conventional power plant with water as working medium. The calculations were made using the assumptions presented in section 3, and the primary assumption for all the variants considered was the maintenance of identical working parameters, i.e. the same temperature of the upper and lower heat source and a constant value of energy flux from fossil fuel.

Based on the calculations performed the following conclusion can be drawn:

- the use of organic medium in a binary power plant allows for an increase of low-temperature geothermal energy share in the total energy flux supplied to the plant and for obtaining measurable benefits in the form of higher power of the power plant.

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Table 1. Summary of selected calculation results for variant primary and binary power plant where organic medium is isobutan

L.p.	t_p^G	t_p^D	t_{od}	Q_d^P	Q_{dod}^P	N_{C-R}^P	η_{C-R}^P	η_{C-R}^{P*}	Q_d^B	Q_{dod}^B	N_{C-R}^B	η_{C-R}^B	η_{C-R}^{B*}
	[°C]	[°C]	[°C]	[kW]	[kW]	[kW]	[%]	[%]	[kW]	[kW]	[kW]	[%]	[%]
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	180	40	43	3085,4	46,0	983,8	31,89	32,37	3217,2	190,4	968,0	30,09	31,98
2	180	45	48	3085,4	66,9	983,8	31,89	32,59	3292,2	286,3	972,4	29,54	32,35
3	180	50	53	3085,4	87,8	983,8	31,89	32,82	3374,1	389,1	978,0	28,98	32,76
4	180	55	58	3085,4	108,7	983,8	31,89	33,05	3463,4	499,4	985,5	28,45	33,25
5	180	60	63	3085,4	129,6	983,8	31,89	33,28	3561,4	618,2	994,8	27,93	33,80
6	180	65	68	3085,4	150,6	983,8	31,89	33,52	3669,0	746,8	1006,3	27,43	34,43
7	180	70	73	3085,4	171,5	983,8	31,89	33,76	3787,8	886,5	1020,1	26,93	35,16
8	180	75	78	3085,4	192,5	983,8	31,89	34,01	3919,6	1039,3	1036,8	26,45	36,00
9	180	80	83	3085,4	213,5	983,8	31,89	34,26	4066,9	1207,6	1056,8	25,99	36,96
10	180	85	88	3085,4	234,5	983,8	31,89	34,51	4233,0	1394,8	1081,0	25,54	38,09
11	180	90	93	3085,4	255,5	983,8	31,89	34,76	4422,4	1605,2	1109,9	25,10	39,40
12	180	95	98	3085,4	276,5	983,8	31,89	35,03	4641,4	1845,2	1145,1	24,67	40,95