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The Influence of Evaporator Parameters on the Effectiveness of Geothermal Power Plant Operation

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ABSTRACT

In the paper presented are the results of calculations of effectiveness of ORC cycle operation at different parameters of supplied geothermal water feeding the evaporator. Calculations encompassing the efficiency and power of ORC cycle will be carried out for different types of organic fluids, which are characterized by different temperatures of evaporation. In all considered cases assumed have been same temperatures of condensation ensuring the comparable heat exchange conditions between condensation and environment. It stems from the preliminary calculations that the effectiveness of operation of geothermal power plant is influenced not only by the effectiveness of C-R cycle but also the extent of its power. The increase of the latter quantity is influenced by the increase of the flow rate of supplied geothermal water. It stems from the calculations also that the efficiency of the C-R cycle does not influence the increase of power of C-R cycle. On that basis the authors of the paper have proposed a new design of the evaporator. As a result of a new a new design evaporation temperature of the working fluid is reduced but the power of the cycle increases due to increase of the flow rate of working fluid in the cycle. Such solution can be applied in the case of pre-heaters and super-heaters. Other ways of increase of effectiveness of operation of geothermal plant have been presented in final conclusions.

1. INTRODUCTION

Geothermal plant, similarly as each installation for production of electricity, is a defined technological system which encompasses a series of nodes and elements where different complex processes are realized. The effectiveness of operation of geothermal plant is influenced by the effectiveness of the entire installation and primarily its power and the extent of utilization of geothermal energy. Published in literature data relate primarily the results of a basic design of the geothermal plant. There is a lack however of a more detailed investigations which would enable wider analysis and assessment of possibility of improvement of power plant operation as a result of actions aimed at increase of its effectiveness. The improvement of effectiveness of operation of such installation can be attained by increase of power and cycle efficiency, but such actions are difficult due to complication of designs between its particular elements. Independently from undertaken directions of actions aimed at improvement of power plant operation efficiency in each case the starting point for such considerations is a wider analysis of operation (effectiveness of operation) of a basic design of geothermal power plant. That has particular importance in case of geothermal waters in Poland due to a fact that temperature of resources at disposal rarely exceed a value of 110°C.

Despite the fact that production of electricity based on ORC cycle is known for several years these were the new substances offered by the chemical industry which opened possibilities of optimization of a low-temperature C-R cycle with the view of reaching its highest effectiveness. In the case of geothermal power plant where temperature of upper and lower heat sources are specified, a key issue is adequate selection of organic fluid. During up to date activities there has been concluded an important influence of some thermophysical parameters of working fluids on the effectiveness of ORC cycle. It has also been found that for fluids for which similar values of the cycle efficiency have been obtained enable to obtain different values of cycle power. It seems that further thermodynamical analysis of ORC cycle is pertinent which could be extended for other fluids of the CF group, silicon oils and zeotropic mixtures.

Elaboration of an effective technology of non-emission conversion of low temperature energy of geothermal water into mechanical energy and further into electricity is highly recommended, as it can improve the profitability of existing geothermal plants as well as newly constructed installations for production of electricity or in combination in thermal energy.

Presented in the present paper results of investigations form an introduction for further investigations, which will also enable, on the basis of an extended analysis of results of investigation, to formulate conclusions related to modernization activities aimed at improvement of effectiveness of operation of geothermal power plant with organic fluids.

2. CHARACTERISTICS OF GEOTHERMAL POWER PLANT

In order to cut down and simplify the description of considered installations as well as the calculation algorithm there has been made an assumption that the considered geothermal water features low salinity and can be directly fed to considered steam cycle installation and treated as a network water. Such water, following reduction of its temperature is fed directly to the pumping well. If the fact is considered that in the case of salinated geothermal water there are used highly efficient counter current heat exchangers then presented in the paper results of calculations can be referenced to geothermal water, temperature of which at the outlet with respect to network water should be higher by $\Delta T=2K$.

In the discussed geothermal power plant the implemented installation has been presented in Fig. 1.

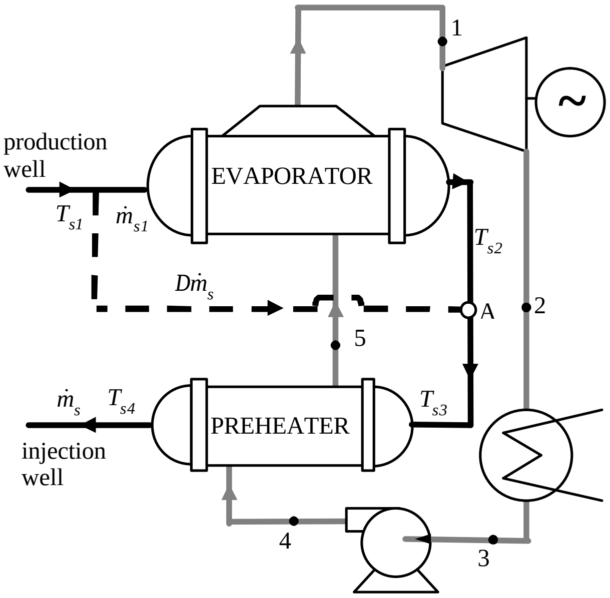

Figure 1: Schematic of power plant with saturated vapour

The power plant operates in line with a C-R cycle. Calculations have been carried out for selected working fluids known as dry ones. Installation in which the cycle processes are realized encompasses the following devices as preheater, evaporator, turbine with generator, condenser and circulation pump. Saturated vapour produced in the evaporator is directed to the steam turbine where isentropic expansion to the pressure present in the condenser takes place. Next, vapour is directed to the condenser where following cooling of superheated vapour its condensation takes place. The condensate of organic fluid is supplying the preheater by means of circulation pump. If assumption is made that all realized processes are pseudo-reversible then we can assume that the sequence of carried out processes corresponds to a comparative C-R cycle for saturated vapour. Such cycle has been presented in the P-h coordinates in Fig. 2.

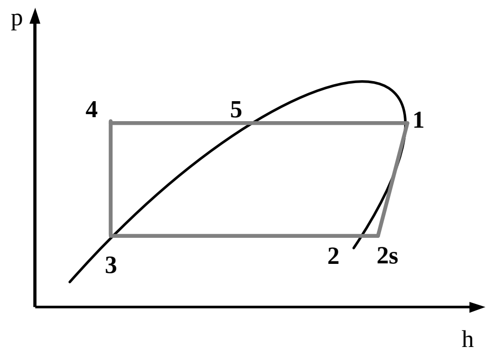

Figure 2: C-R cycle for a power plant with saturated vapour

3. BASIC RELATIONS USED IN THE CALCULATION ALGORITHM

3.1 Methodology of Calculation of Calorific Parameters of State

In order to determine values of specific enthalpies which are present in relevant relations of calculation algorithm there ought to determined particular values of enthalpy. In relation to the above for particular organic fluids the following procedure has been applied based on data base NIST:

a. on the basis of network water temperature there can be established evaporation temperature which will feature a corresponding evaporation pressure, which in such case is equal to

$$P = P_1 = P_4 = P_5 \tag{1}$$

b. for such evaporation pressure determined have been subsequently the following enthalpies and specific entropy

$$h_5 = f(P_5, x_5 = 0) \tag{2}$$

$$s_5 = f(P_5, x_5 = 0) \tag{3}$$

$$h_1, s_1 = f(P_1, x_1 = 1) \tag{4}$$

c. next, on the basis of data related to the condenser there ought to be established condensation temperature and corresponding to that temperature saturation pressure, which is equal to

$$P = P_3 = P_2 = P_{2s} \tag{5}$$

d. enthalpy and entropy for state 2s using the isentropic expansion 1-2s for which s1=s2s there can be determined:

$$h_{2s} = f(P_2, s_{2s} = s_1) \tag{6}$$

e. enthalpy h2 for the state 2 determined has been on a basis of condensation pressure P3=P2 for x=1 whereas in state 3 the enthalpy h3 for condensation pressure P3 and x3=0.

In calculations it has been assumed that in the preheater of organic fluid there has been applied a counter current heat exchanger with equal rates of thermal capacities of fluids. Subsection headings should be capitalized on the first letter.

3.2 A Power Plant with Dry Organic Fluid on Saturated Vapour

Presented below have been particular relation used in calculations of a power plant for saturated vapour when $D\dot{m}_s = 0$, a schematic of which has been presented in Fig. 1. Rate of heat supplied with network water to the evaporator

$$\dot{Q}_{par} = \dot{m}_s c_s (T_{s1} - T_{s2}) \tag{7}$$

Rate of heat removed by the organic fluid in evaporator

$$\dot{Q}_{par} = \dot{m}_n (h_1 - h_5) \tag{8}$$

Rate of mass of organic fluid, determined from the energy balance equation using relations (1) and (2), is defined by the formulae

$$\dot{m}_n = \dot{m}_s \frac{c_s (T_{s1} - T_{s2})}{(h_1 - h_5)} \tag{9}$$

Rate of heat transferred by network water in the heater

$$\dot{Q}_{pod} = \dot{m}_s c_s (T_{s3} - T_{s4}) \quad (10)$$

Rate of heat removed in heater by the organic fluid liquid during heating from condensation temperature to evaporation temperature

$$\dot{Q}_{pod} = \dot{m}_n (h_5 - h_4) = \dot{m}_n c_n (T_5 - T_4) \quad (11)$$

Energy balance equation of heater stemming from equating relations (10) and (11) has a form

$$\dot{m}_s c_s (T_{s3} - T_{s4}) = \dot{m}_n (h_5 - h_4) \quad (12)$$

Using the counter current heat exchanger and assuming a complete regeneration of heat at constant temperature difference between the heat carriers a condition of equality of both rates of heat is attained

$$\dot{W}_s = \dot{W}_n \quad (13)$$

or

$$\dot{m}_s c_s = \dot{m}_n c_n = \frac{h_1 - h_5}{T_{s3} - T_{s4}} \quad (14)$$

If

$$\dot{m}_{s1} c_s < \dot{m}_n \frac{h_1 - h_5}{T_{s3} - T_{s4}} \quad (15)$$

Then in order to obtain a full regeneration of heat in heater there ought to be a part of mass flow rate of network water ms directed to the heater through a special by-pass. As a result of such operation the evaporator will be supplied with a lower flow rate of network water equal to

$$\dot{m}_s = \dot{m}_{s1} + D\dot{m}_s \quad (16)$$

or

$$D\dot{m}_s \neq 0 \quad (17)$$

Energy balance equations:

In evaporator

$$\dot{m}_n (h_1 - h_5) = (\dot{m}_s - D\dot{m}_s) c_s (T_{s1} - T_{s2}) \quad (18)$$

In node A

$$\dot{m}_s c_s T_{s3} = (\dot{m}_s - D\dot{m}_s) c_s T_{s2} + D\dot{m}_s c_s T_{s1} \quad (19)$$

In preheater

$$\dot{m}_n (h_5 - h_4) = \dot{m}_s c_s (T_{s3} - T_{s4}) \quad (20)$$

Following the solution of the above set of equations (16,18,19,20) the expression for the mass flow rate of network water in the by-pass takes a form

$$D\dot{m}_s = \dot{m}_s \left[\frac{c_s (T_{s1} - T_{s4})}{h_1 - h_4} - \frac{T_{s2} - T_{s4}}{T_{s1} - T_{s2}} \right] \quad (21)$$

$$\dot{m}_n = \dot{m}_s \frac{c_s (T_{s1} - T_{s4})}{h_1 - h_4} \quad (22)$$

3.3 C-R Cycle Characteristic Quantities

A unit work of the cycle

$$l_{C-R} = h_1 - h_{2s} \quad (23)$$

Cycle efficiency

$$h_{C-R} = \frac{h_1 - h_{2s}}{h_1 - h_4} \quad (24)$$

Power of the cycle

$$N_{C-R} = \dot{m}_n (h_1 - h_{2s}) \quad (25)$$

4. RESULTS OF CALCULATIONS

Table1 Tabulation of output data to the first stage of analysis

T_{s1} °C	T_1 °C	$\dot{m}_{s1}$ kg/s	$\dot{Q}_{par}$ kW
50	40	45.16	1887.9
60	50	45.58	1905.2
70	60	45.96	1921.2
80	70	46.13	1935.8
90	80	46.63	1949.2
100	90	46.92	1961.3

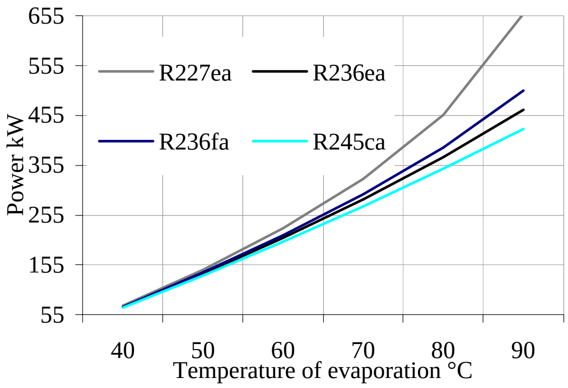

Figure 3: Power of vapour plant in function of fluid evaporation temperature at variable rate of heat supplied in evaporator

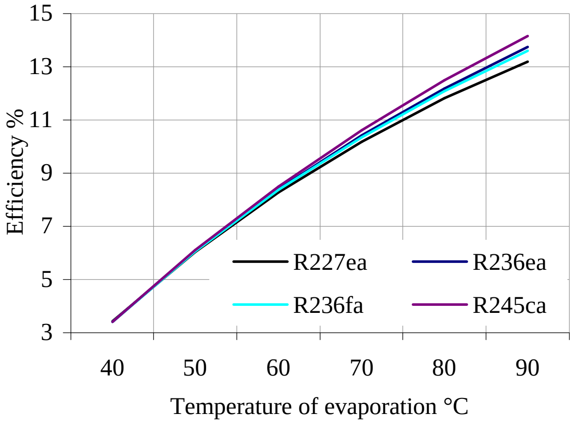

Figure 4: Efficiency of vapour plant in function of fluid evaporation temperature

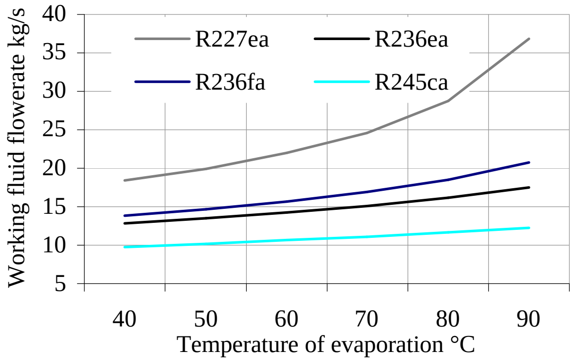

Figure 5: The flow rate of working fluid in function of fluid evaporation temperature at variable rate of heat supplied to the evaporator

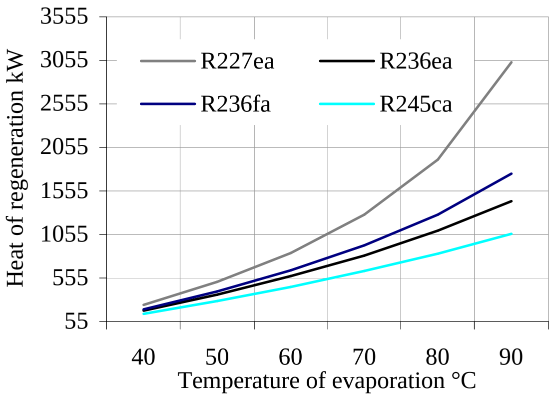

Figure 6: The rate of regeneration heat (supplied to the heater) in function of fluid evaporation temperature at variable rate of heat supplied to the evaporator

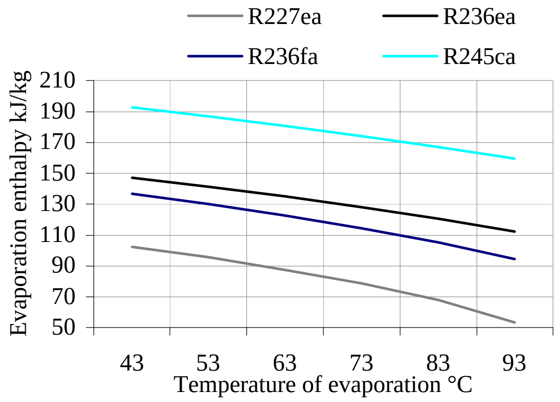

Figure 7: Evaporation enthalpy of working fluid in function of evaporation temperature

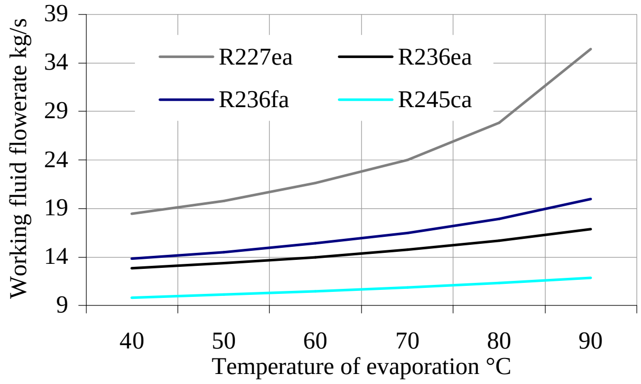

Figure 8: Vapour plant power in function of fluid evaporation temperature at constant rate of heat supplied in the evaporator (1887.9 kW)

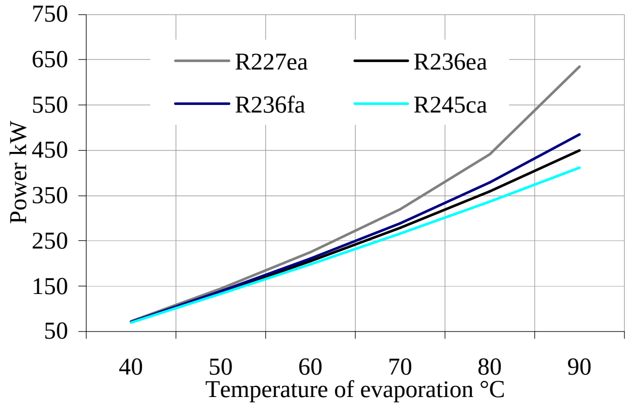

Figure 9: Flow rate of working fluid in function of fluid evaporation temperature at constant rate of heat supplied in the evaporator (1887.9 kW)

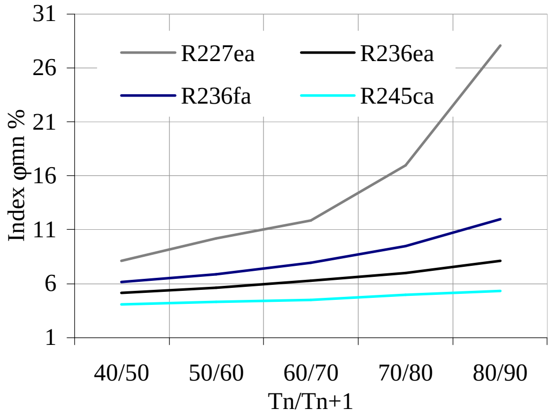

Figure 10: Percentage indicator φ_{mn} of mass flow rate increase of working fluid for subsequent evaporation temperatures of fluid.

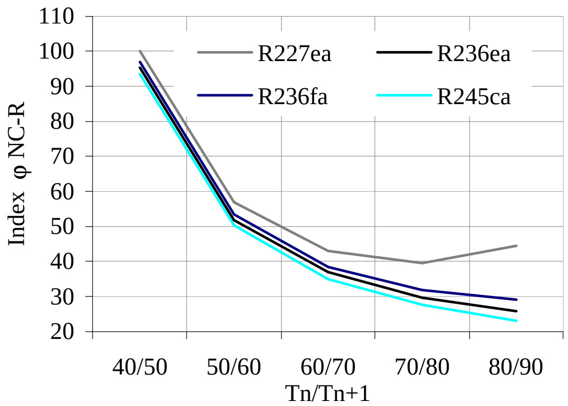

Figure 11: Percentage indicator φ_{NCR} depicting the reduction of power for subsequent evaporation temperatures of working fluid

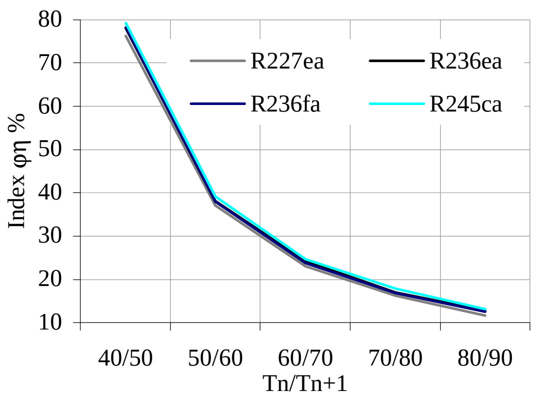

Figure. 12 Percentage indicator φ_{η} of reduction of C-R cycle efficiency for subsequent fluid evaporation temperatures

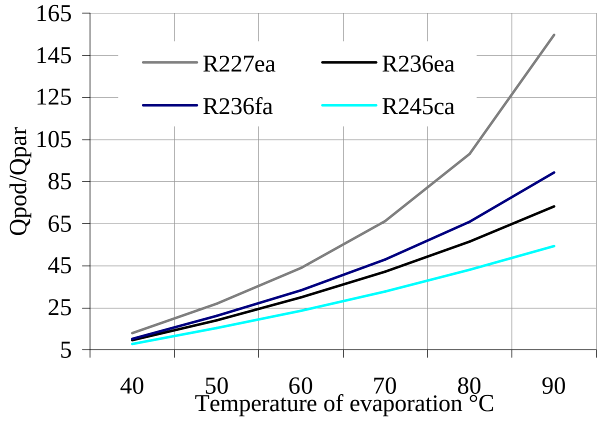

Figure 13: Indicator of heat regeneration as a ratio of rate of regeneration heat $\dot{Q}_{pod}$ to evaporation heat $\dot{Q}_{par}$

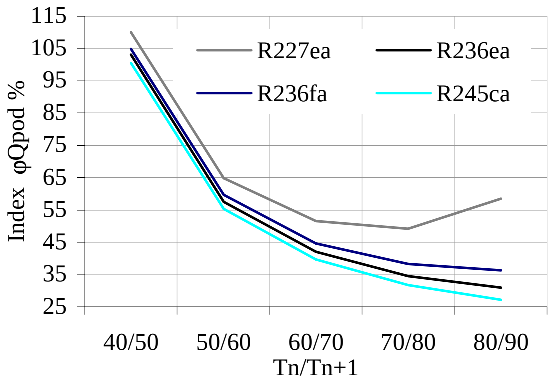

Figure 14: Indicator j_{Qpod} of heat regeneration for subsequent fluid evaporation temperatures

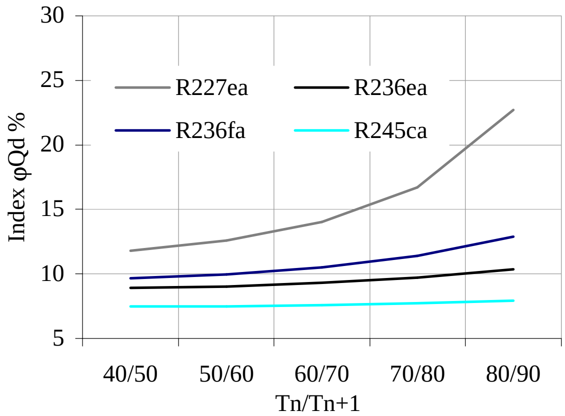

Figure 15: Indicator φ_{Qd} depicting a percentage increase of a total heat supplied to C-R cycle for subsequent fluid evaporation temperatures

5. GENERAL CONCLUSIONS

On the basis of analysis of the results of calculations presented above the following conclusions, presented below, have been formulated:

1. In the case of both groups of fluids, where similar values of C-R cycle efficiency were present, different values of power have been obtained. The highest values of C-R cycle power are obtained in the case of these fluids for which evaporation temperature is close to critical temperature of particular fluid.
2. The effectiveness of utilisation of geothermal energy is influenced also by a value of return temperature of network water. Its reduction is increasing with the extent of heat recovery in the heater of organic fluid. Such effect can be obtained using multi-pass vapour plants with a serial supply of particular heat exchangers, i.e. superheaters, evaporators and heaters.
3. Improvement of effectiveness of operation can be obtained by using the reversal of a mass flow rate of water from the exchanger outlet, combining in such way this flow rate with a flow rate of water at inlet to that exchanger. That refers to all outlined earlier exchangers. A way to solve that problem have been presented in Borsukiewicz-Gozdur and Nowak (2007)
4. Another way to increase effectiveness of operation of steam plant with organic fluid can be replacement of single component power plant with a binary power plant with two loops, of which in the upper circuit water is the working fluid whereas in the lower circuit the organic fluid. A way to solve that problem, with account of thermal coupling of both circuits in the heat exchanger of evaporator-condenser type have been presented in Nowak et. al. (2006).
5. Effectiveness of operation of power plant can also be increased as a result of increasing temperature of network water. Application of simple solutions as a result of supply of external heat does not return expected effects of power increase with respect to supplied heat..

Therefore there ought to be applied solutions where combined production of electricity and heat is used. For example these can be CHP units or sets of gas turbines cooperating with a geothermal power plant.

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