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Geothermal Power Station with Supercritical Organic Cycle

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ABSTRACT

Geothermal water at moderate temperatures can be used for the supplying or co-supplying of a thermal plant or a power plant. In the latter case, Organic Rankine Cycle (ORC) plants operating with subcritical parameters are usually applied. The alternative to such a design is the ORC power plant operating with supercritical parameters supplied by moderate temperature geothermal water.

A schematic of such installation is presented here with a description of its operation and the algorithm of calculations of a supercritical power plant. An analysis of the influence of a kind of working fluid on the effectiveness of operation of a plant was carried out. In this analysis, geothermal water temperatures varying in the range T_{g1}=95-120°C and a constant flow rate of 15 kg/s were assumed. Results of calculations have shown that the highest values of efficiency and power were used in the case where propylene was a working fluid. A comparison of a supercritical cycle power plant and an appropriate subcritical ORC power plant was attempted under the assumption of comparable conditions of supply and removal of heat to and from the system. The obtained results enabled the unanimous conclusion that the application of supercritical conditions in low-temperature ORC installations of geothermal plants allows significantly higher values of both efficiency and power to be achieved.

1. INTRODUCTION

Geothermal water at moderate temperatures can be used to supply or co-supply heat and/or power to thermal plants or power plants. In the latter case, Organic Rankine Cycle (ORC) plants operating with a subcritical cycle are usually applied (DiPippo, 2005; Borsukiewicz-Gozdur and Nowak, 2007; Hettiarachchi et al., 2007).

A good alternative to this design is an ORC power plant operating at supercritical conditions and supplied with moderate temperature geothermal water. The power plants featuring supercritical parameters are becoming more popular in conventional power engineering. In the case of a geothermal power plant, an interesting contribution was encountered regarding the application of CO_2 with supercritical parameters in a demonstration power plant supplied with geothermal heat in Oradea, Romania. Gu and Sato (2001) carried out an analysis of the effectiveness of the application of propane as a working fluid in a power plant supplied with geothermal water at 229.4°C. In subsequent works, Gu and Sato (2002) conducted an analysis of the effectiveness of the application of working fluids such as propane, R125 and R134a in an ORC plant supplied with geothermal water at the same temperature. In both contributions, the results of analyses have been referred to a reference power plant described by Kanoglu (1999). In the present paper, a comparative analysis of application of different working fluids in a supercritical cycle ORC is presented, and the results are compared to an analogous subcritical power plant. It is worth stressing that this analysis regards the possibilities of management of low-temperature geothermal water.

2. DESCRIPTION OF INSTALLATION AND PRINCIPLES OF OPERATIONS OF A POWER PLANT

A schematic of a supercritical cycle ORC power plant supplied with energy of geothermal water is presented in Figure 1. It operates in line with a comparative Clausius-Rankine (C-R) cycle consisting of two isobars and two isentropes. The cycle of thermodynamic processes is illustrated in the T-s diagram presented in Figure 2.

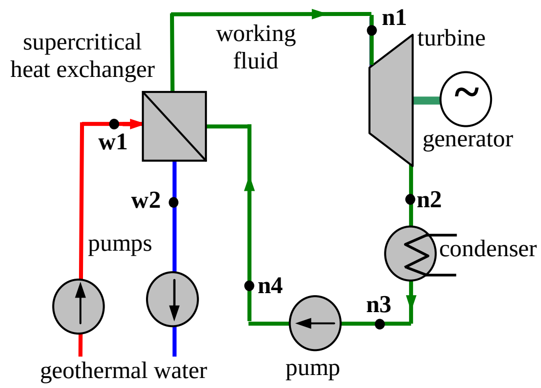

Figure 1. Schematic of a geothermal power plant with a supercritical cycle

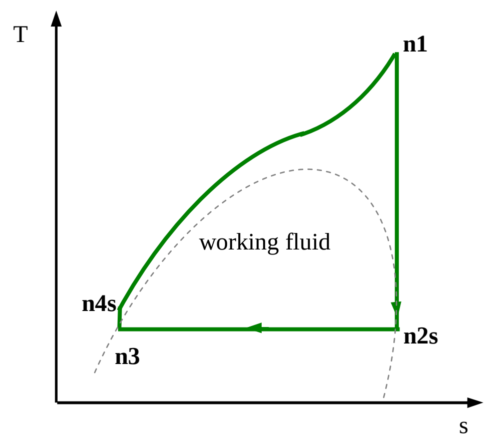

Figure 2. The cycle of thermodynamic processes in a supercritical power plant operating according to the Clausius-Rankine cycle

The installation under scrutiny here consists of the following devices:

- vapor turbine driving the generator, where the isentropic process of expansion (1-2s) is accomplished,
- condenser of organic fluid, where isobaric process of heat removal is carried out (2s-3),
- circulation pump, where the process of isentropic compression of liquid from the pressure $p_{2s}=p_3$ to pressure p_{4s} (3-4s) is realized;
- adiabatic heat exchanger, where the isobaric transfer of heat from hot water to organic fluid occurs (4s-1).

The transfer of heat in the exchanger takes place under pressure $p_{4s}=p_1>p_{cr}$,, which is appropriately higher than the critical pressure of working fluid p_{cr} – and hence, it will be referred to as a supercritical heat exchanger. The organic vapor produced in this counter-current heat exchanger with parameters $p_1>p_{cr}$ and $T_1> T_{cr}$ is directed to the turbine. It has been assumed that isentropic expansion always takes place to reach the state of saturated vapor (i.e. the end of expansion falls into the location of x=1). For all fluids, the condensation temperature of working fluid is assumed to be T_{2s}=30°C, and the heat of condensation is removed to the surroundings using a flow of air or another cooling substance. Calculations have been performed for four selected organic fluids, namely R115, R125, R143a, and propylene, and the principal criterion of their selection were sufficiently low critical parameters.

3. ALGORITHM OF CALCULATIONS

Respective specific quantities characterizing the comparative C-R cycle referring to a unit amount of organic fluid (working fluid) can be determined from the relations given below:

- specific isentropic technical work of decompression

$$l_{t1-2s} = h_{n1} - h_{n2s} \tag{1}$$

- specific rate of heat removed in the condenser

$$q_{2s-3} = h_{n2s} - h_{n3} \tag{2}$$

- specific technical work of pumping

$$l_{t3-4s} = h_{n4s} - h_{n3} \tag{3}$$

- specific rate of supplied heat

$$q_{4s-1} = h_{n1} - h_{n4s} \tag{4}$$

On the basis of the above relations, the specific work of the C-R cycle can be determined as:

$$l_{C-R} = l_{t,1-2s} - l_{t,3-4s} \tag{5}$$

Efficiency of C-R cycle:

$$\eta_{C-R} = \frac{l_{C-R}}{q_{4s-1}} \tag{6}$$

In order to determine the power of comparative Clausius – Rankine cycle N_{C-R}, the flow rate of fluid in circulation $\dot{m}_n$ in a supercritical cycle must also be determined. Bearing that in mind, a schematic of a supercritical heat exchanger with temperature distributions is presented in Figure 3. The energy balance for this exchanger was completed on this basis.

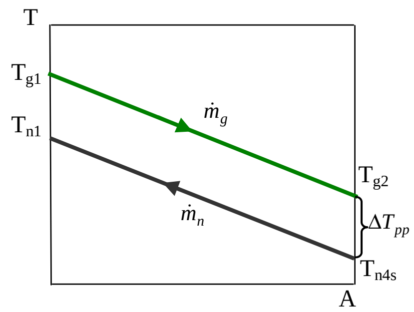

Figure 3. Schematic of a supercritical heat exchanger with temperature distributions of respective fluids

The energy balance for a supercritical heat exchanger yields:

$$\dot{Q}_s = \dot{m}_g c_g \left(T_{g1} - T_{g2}\right) = \dot{m}_n c_n \left(T_{n1} - T_{n4s}\right) \tag{7}$$

Due to the accuracy of calculations and availability of particular data, especially from the side of working fluid, it is much easier to carry out calculations using the respective specific values of enthalpies:

$$\dot{Q}_s = \dot{m}_n \left(h_1 - h_{4s}\right) \tag{8}$$

In calculations for a supercritical heat exchanger, the pressure drop of the working fluid has been neglected, and it was assumed that ΔT_{pp} =5 K.

As can be seen in Figure 3, it was also assumed that the rates of thermal capacities of both fluids are equal, which is described in Equation (9):

$$\dot{W}_s = \dot{W}_n \tag{9}$$

where

$$\dot{W}_n = \dot{m}_n \bar{c}_n \tag{10}$$

$$\dot{W}_s = \dot{m}_s \bar{c}_s \tag{11}$$

By utilizing parametric data of the geothermal water (including mass flow rate), the mass flow rate of fluid in the cycle can be determined using Equation (12)

$$\dot{m}_n = \frac{\dot{m}_g \bar{c}_g \left(T_{g1} - T_{g2}\right)}{h_{n1} - h_{n4s}} \tag{12}$$

On the basis of thermal and calorimetric parameters of state from Refprop 7.0 at characteristic points in the C-R cycle, the level of theoretical power can be determined according to Equation 13:

$$N_{C-R} = \dot{m}_n \left(l_{t,1-2s} - l_{t,3-4s}\right) \tag{13}$$

4. RESULTS OF CALCULATIONS

The values of temperatures and specific enthalpies at characteristic nodes of the cycle are presented in Table 1 for the working fluids considered – i.e. R115, R125, R143a, and propylene. These quantities and the assumed parameters of geothermal water serve as a basis for subsequent calculations of efficiency, power of installation, and other parameters.

It should also be noted that the end of the expansion process in the turbine is located on the saturation vapor line coinciding with temperature T_{n2s}=30°C. In relation to the temperature values assumed above for particular fluids, the resulting working pressure ranges were amended and are presented in detail in Table 2.

Table 1: Values of temperatures and specific enthalpies at characteristic points of the cycle for selected fluids

T_{g1}	T_{n1}	h_{n1}	T_{2s}	h_{2s}	T_3	h_3	T_{4s}	h_{4s}
R125 (T_{cr}=66.02°C, p_{cr}=3.61 MPa)								
95	90	360.1					33.4	242.8
100	95	361.2					33.8	243.2
105	100	362.4	30	344.7	30	239.9	34.3	243.7
110	105	363.7					34.9	244.8
115	110	365.1					35.6	245.0
120	115	366.8					36.4	245.8
R134a (T_{cr}=72.71°C, p_{cr}=3.76 MPa)								
95	90	422.1					32.8	250.7
100	95	423.6					33.1	251.1
105	100	425.2	30	400.1	30	247.6	33.5	251.5
110	105	426.7					33.8	252.0
115	110	428.3					34.3	252.5
120	115	429.9					34.7	253.1
R115 (T_{cr}=79.95°C, p_{cr}=3.12 MPa)								
95	90	336.3					32.3	234.0
100	95	337.1					32.6	234.2
105	100	337.9					32.9	234.6
110	105	338.8					33.3	234.9
115	110	339.8					33.8	235.4
120	115	340.9	30	323.0	30	232.0	34.4	236.0
propylene (T_{cr}=92.42°C, p_{cr}=4.66 MPa)								
95	90	649.8					32.0	281.9
100	95	653.1					32.2	282.5
105	100	656.4					32.4	283.1
110	105	659.6					32.7	283.7
115	110	662.7					33.0	284.4
120	115	665.8	30	602.1	30	277.2	33.2	285.1

Table 2: Ranges of working pressures for particular cases of calculations

	R125 $p1=p_{4s}$=1.5685 MPa		**R143a** $p1=p_{4s}$=1.4340 MPa	
T_{g1} °C	p3=p2s MPa	Δp MPa	p3=p2s MPa	Δp MPa
95	4.9748	3.4063	4.2745	2.8405
100	5.4763	3.9078	4.6425	3.2085
105	6.0595	4.4910	5.0461	3.6121
110	6.7508	5.1823	5.4924	4.0584
115	7.5868	6.0180	5.9907	4.5567
120	8.6146	7.0461	6.5530	5.1190
	R115 $p1=p_{4s}$=1.0284 MPa		**propylene** $p1=p_{4s}$=1.3084 MPa	
T_{g1} °C	p3=p2s MPa	Δp MPa	p3=p2s MPa	Δp MPa
95	3.5508	2.5224	3.6564	2.3480
100	3.8912	2.8628	3.9395	2.6311
105	4.2927	3.2643	4.2401	2.9317
110	4.7796	3.7512	4.5597	3.2513
115	5.3884	4.3600	4.9006	3.5922
120	6.1735	5.1451	5.2655	3.9571

The distributions of thermal efficiency and theoretical power of the C-R cycle are presented in Figures 4 and 5 as a function of geothermal water temperature for the selected fluids.

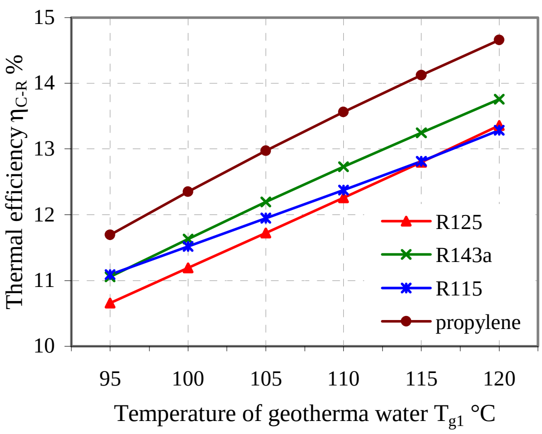

Figure 4: Thermal efficiency of C-R cycle in function of geothermal water temperature T_{g1} for selected working fluids

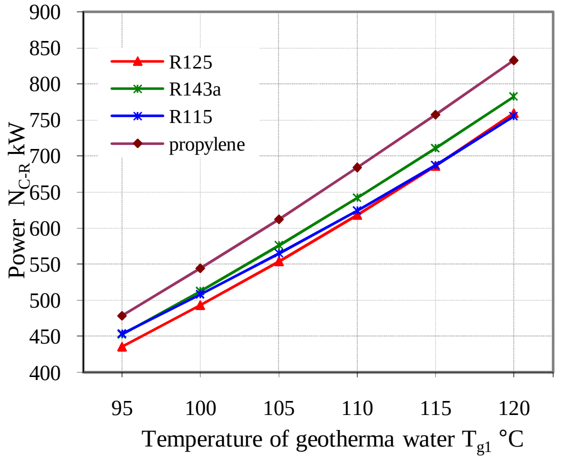

Figure 5: Theoretical power of C-R cycle in function of geothermal water temperature T_{g1} for selected working fluids ($\dot{m}_g$ =15 kg/s)

As can be seen in Figures 4 and 5, both efficiency and power increase with the temperature of the heat source. For the fluids R143a, R115 and R125, very close values of efficiency and power were obtained (for a given temperature of geothermal water). In the case of propylene, the efficiency was about 1% higher than that obtained for all other working fluids. The theoretical power was also noticeably higher when using propylene as the working fluid.

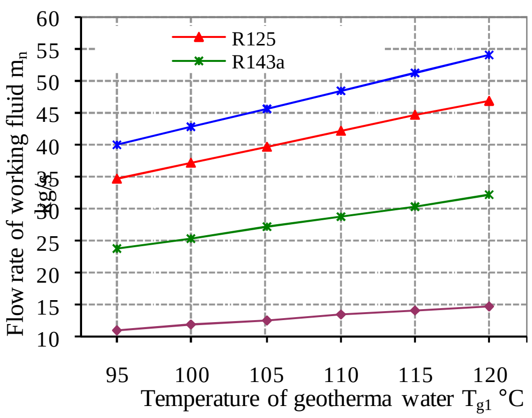

Figure 6: Mass flow rate of working fluid in the C-R cycle as a function of geothermal water temperature T_{g1} for selected working fluids ($\dot{m}_g$ =15 kg/s)

The values of expansion and pumping work are presented in Figures 7 and 8 as a function of geothermal water temperature for different fluids, and the percentage comparison of shares of each type of work is presented in Figure 9 for a geothermal water temperature of 100°C.

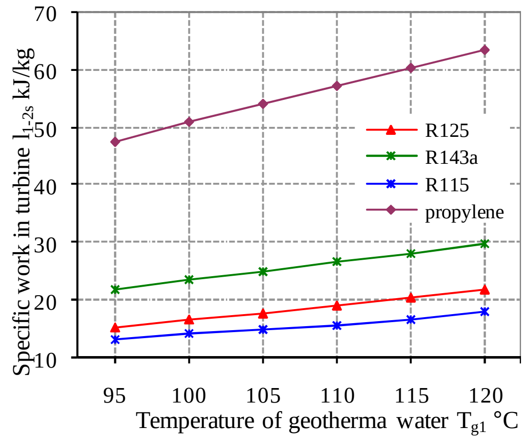

Figure 7: Specific work in turbine as a function of geothermal water temperature T_{g1} for selected working fluids

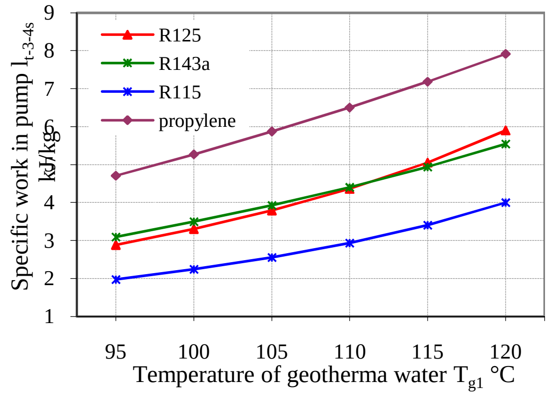

Figure 8: Specific technical work supplied to pump as a function of geothermal water temperature T_{g1} for selected working fluids

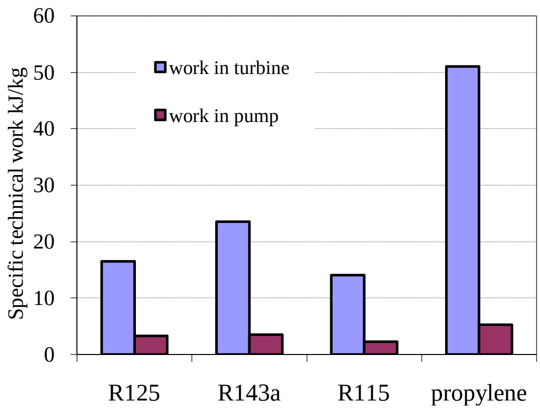

Figure 9: Percentage shares of work in turbine and pumps for selected working fluids (at a geothermal water temperature of T_{g1}=100°C)

5. CONCLUSIONS

In the frame of the present work, theoretical calculations of an ORC power plant with supercritical parameters were carried out for different working fluids. It was assumed that geothermal water temperature ranged from 95 to 120°C, with a constant mass flow rate of 15 kg/s. Four organic fluids with sufficiently low critical parameters were selected as candidate working fluids in the plant. Calculations of efficiency and power of this supercritical power plant were performed, and propylene was found to have the most favorable values of both parameters.

The results of calculations of efficiency and theoretical power obtained for a geothermal plant with subcritical parameters (typical ORC plant) are presented in Table 3, where a comparative supply and removal of heat were assumed.

Table 3: Results of calculations of efficiency and theoretical power of a plant with subcritical parameters for comparative conditions of heat supply and removal in a geothermal power plant

	T_{g1}=95°C	T_{g1}=105°C	T_{g1}=115°C
R115			
$\eta_{sub,C-R}$ %	7.54	8.24	8.83
$N_{sub,C-R}$ kW	112.62	162.42	228.90
R236fa			
$\eta_{sub,C-R}$ %	8.12	10.14	11.89
$N_{sub,C-R}$ kW	202.68	280.65	369.08
R227ea			
$\eta_{sub,C-R}$ %	8.02	9.96	11.61
$N_{sub,C-R}$ kW	216.38	310.18	431.03

An analysis of the effectiveness of operation of a plant with supercritical and subcritical parameters was conducted on the basis of the power and efficiency of the theoretical C-R cycle. Both the efficiency and power of a plant with supercritical parameters are significantly higher than those of a power plant with subcritical parameters for all geothermal water temperatures considered. Efficiency values of a plant with supercritical parameters vary from 10.5% to 14.5%, compared to the respective efficiency range of 7.5% to 11.9% for a subcritical power plant.

The power of an ORC plant with subcritical parameters is 40% to 78% lower than that of a plant operating with supercritical parameters. This is most likely due to the fact that the rate of geothermal heat supplied to the supercritical plant is much higher than that supplied to the subcritical plant. This, in turn, leads to a much higher flow rate of working fluid in the supercritical plant than that in the subcritical plant. For example, the values obtained for flow rate of the working fluid R115 in the subcritical plant is as much as three fold lower (for T_{g1}=95°C) than that in the supercritical plant.

It should be noted that the largest difference between the power supplied by a subcritical plant and that supplied by a supercritical plant was found to occur at lower temperatures of geothermal water.

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