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Effect of the Working Medium on the Thermodynamic Efficiency of Geothermal Power Stations

Andriy REDKO, Nataliia KULIKOVA, Sergiy PAVLOVSKYI, Volodymyr BUGAI, Oleksandr REDKO

Kharkiv National University of Civil Engineering and Architecture, Kharkiv, 61002, Ukraine

E-mail: andrey.ua-mail@rambler.ru

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ABSTRACT

Results of a numerical study on the cycle efficiency for different working mediums are given. The efficiencies of using R141 and R161b mixtures in supercritical binary cycles are shown.

1. INTRODUCTION

Ukraine possesses significant sources of geothermal energy that are estimated to be at $3.4x10^{11}$. The priority directions for the development of Ukraine geothermal power are the construction of the GeoPS with the capacity of 10 to 50 MW on the basis of high temperature fields having geothermal fluid temperatures that are more than 150°C, as well as small-sized power stations with capacities between 50 to 5000 kW, and the construction of combined fuel geothermal power stations.

One of the problems in making efficient GeoPS heat-schemes is the choice for the working fluid, which will carry the heat. Currently, organic substances (isobutane, pentane, hexane, isobutane-isopentane mixture), cooling agents (R142b, R143a, R134a and others), water-ammonia mixtures, and others are widely used. The search for efficient working mediums is still ongoing.

2. THE PRESENT STATE-OF-ART

The choice of a working medium for a geothermal power station is determined based on various requirements. The most important of these are: relatively high thermodynamic Rankine-cycle efficiency, minimal weight and mass indices of steam power equipment, environmental safety, and suitable operating characteristics. Moreover, the important parameter of the GeoPS heat scheme is the operation of vapor expansion in the turbine with electric power being generated based on the geothermal fluid rate.

Based on a literature review, the list of parameters affecting the electrical power output of a geothermal power station includes the following: pressure and temperature of the steam in front of the turbine, thermodynamic and physical properties of the working medium; working medium rate; rate and temperature of the thermal fluid; the value of Δt_{min} (minimal temperature head) in the evaporator and condenser; ambient temperature; and the inner turbine efficiency of the turbine and the pumps.

The results from previous studies [2-10] show that isobutane, isobutane-and-isopentane mixture, and the cooling agent R142b are the most widely used working mediums. The specific electric power generation values at the temperature of 180°C are: 71.9 kW•s/kg for R142b; 66.2 kW•s/kg for the isobutane-isopentane mixture (90/10), and 76.6 kW•s/kg for isobutane. Using mixtures at supercritical conditions enables one to control the thermodynamic parameters of a working medium by changing the mixture composition. The analysis of supercritical cycles for high temperature thermal waters show that the supercritical cycle, being similar to the triangle cycle, is the most effective one in terms of generating the maximum electric power. The objective of this study is to investigate the effects of different working mediums based on properties that affect the thermodynamic efficiency of a geothermal power station.

3. RESULTS AND DISCUSSION

Supercritical cycles for more than 50 working mediums including ammonia (R717), n-hexane (R602), R600a/R141b mixture, R600a/R161 mixture, isobutane/isopentane mixture, and others were studied for the working GeoPS cycle. The following requirements were made to the working cycle medium: low normal boiling point temperature (less than 350K), large evaporation heat, high density, the shape of right boundary curve (the line of the saturated vapor) at the temperature-entropy diagram (i.e. the vapor parameter value must be confined after its expansion in the turbine) and other suitable operating characteristics. There were some limitations in choosing the appropriate working medium. The limitations were connected with ecological and technological standards, as well as safety requirements. The power generation capabilities and the environmental and safety effects were considered at the same time when the working medium was chosen.

In the calculations, the following limitation was specified: the vapor expansion processes in the turbine (steps 3 to 4) must be completed in the single phase region (Figure 1).

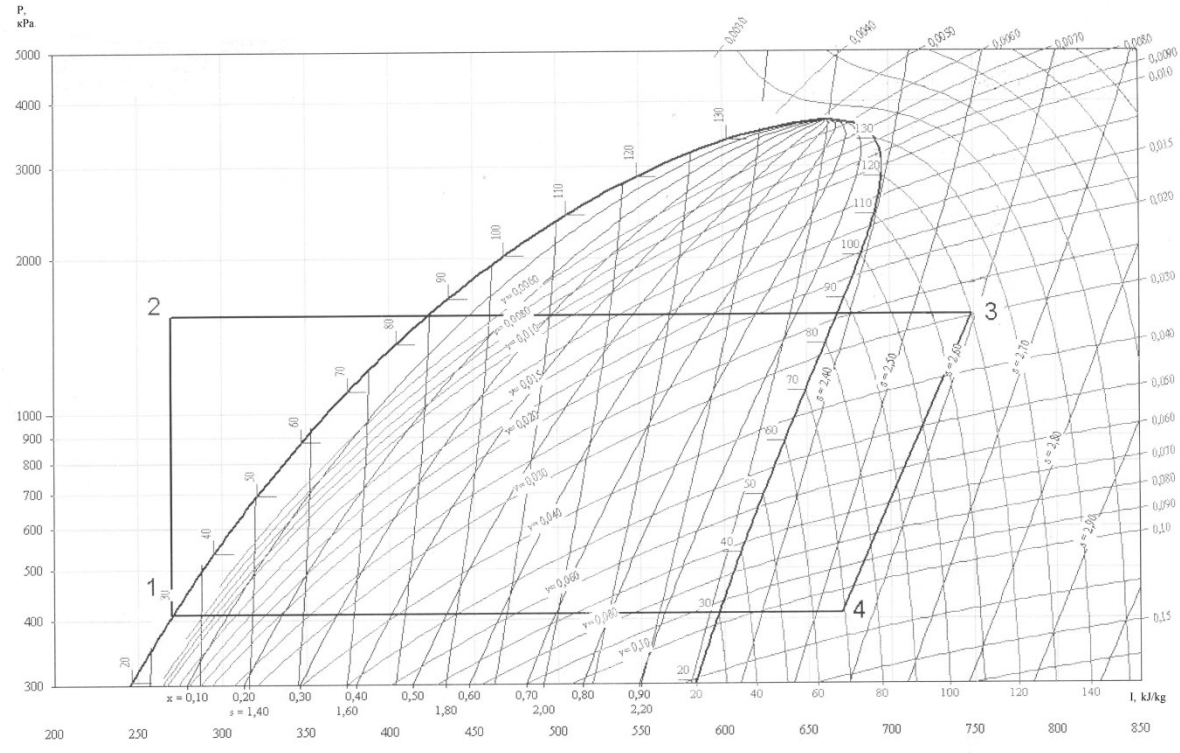


Figure 1. The pressure – enthalpy diagram for the geothermal binary GeoPS cycle (1-2 – compression in the pup; 2-3 – heating and evaporation; 3-4 – expansion in the turbine; 4-1 – vapor cooling and condensation).

The coefficient of thermal fluid performance (COP) is defined as follows:

$$COP = \frac{L_{1,2} - L_{3,4}}{Q_{2,3}} \tag{1}$$

where,

L1,2 and L3,4 are from the adiabatic compression (expansion) in the pump (1-2) and in the turbine (3-4)

Q2,3 – the amount of heat in the isobaric process.

The coefficient of heat utilization in the cycle is defined by:

$$\eta_{h.u} = \frac{W}{m_T\left[(i_{T'} - i_0) - T_0(S_{T'} - S_0)\right]} \tag{2}$$

where,

W is the power of energy station;

T is the temperature of the thermal fluid;

I is the enthalpy; and

S is the entropy of the thermal fluid.

Some results of numeral investigations of a GeoPS working cycle having different working mediums are given in Table 1.

Table 1. Main parameters of GeoPS working cycle

Working medium	t_3, °C	t_4, °C	P_3, *kPa*	P_4, *kPa*	ρ_3, *kg/m³*	$W_{3\text{-}4}$, *kW·s/kg*	*COP*, *%*
Subcritical cycle							
R600a/n-hexane	197	114,9	3850	197	116	64,0	13.99
R600a/R161	197	132,7	3600	489	61,0	85,3	13.10
R600a/R141b	197	140,5	2500	280	49,5	74,5	12.89
	197	124,6	3700	280	82,8	92,7	14.48
Supercritical cycle							
R600a/n-hexane	197	76,3	6000	197	278,6	92,2	13.64

R600a/R161	197	106,0	6000	489	119,8	108,3	15.08
R600a/R141b	197	95,3	6000	280	177,0	108,4	15.55

Useful electric power being generated in the supercritical cycle increases by 15 to 18% when the density of a working medium in front of the turbine is 2.4 to 3.0 times larger than in the subcritical cycle. This allows the overall size of the steam turbine unit to be lowered. The cycle efficiency changes in the range of 12.8 to 15.6% and the ratio of using geothermal fluid to heat is 38.5% for a subcritical cycle, 41.7% for a near-critical cycle, and 91 to 92% for the supercritical one.

Mixtures of i-C4H10 (R600a)/R141b and i-C4H10 (R600a)/R161b are effective working mediums. Figure 2 shows the boundary curves for i-C4H10 and the C4H10/R141b mixture in P-I coordinates.

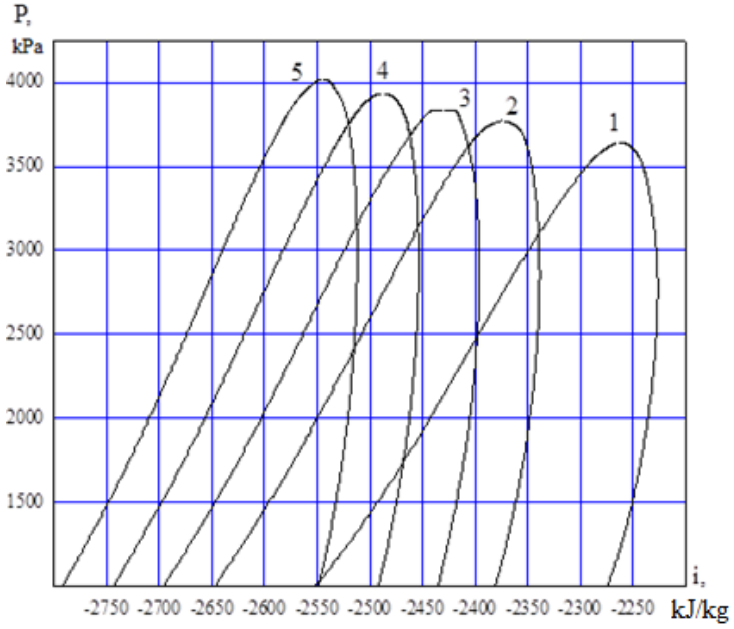


Figure 2. The plot of P-i for i-C4H10 and mixture (C4H10/R141b). 1 – iC4H10 (pure); 2 – iC4H10 (80% mass.) + R-141b (20% mass.); 3 – iC4H10 (70% mass.) + R-141b (30% mass.); 4 – iC4H10 (60% mass.) + R-141b (40% mass.); 5 – iC4H10 (50% mass.) + R-141b (50% mass.).

The effect of mixture concentration on the value of electric power being generated is presented in Table 2.

Table 2. The value of COP and the coefficient on heat utilization for different mixture concentrations

Mixture concentration R600a/R161,%	COP,%	$\eta_{h.u}$,%
50/50	14,10	90,6
60/40	14,09	92,0
70/30	14,13	92,05
80/20	14,04	92,08

The analysis and calculation of results show that the optimal cycle parameters are obtained for the mixture R600a/R161 with a concentration of 70/30%, which leads to a conversion COP ratio approaching up to 13 to 14 %. The graphical dependence of COP on the vapor pressure of the mixture (i-C4H10/R141) in front of turbine is given in Figure 3.

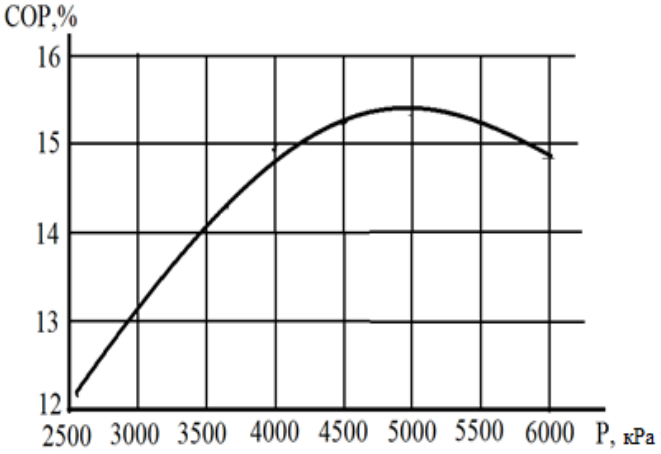


Figure 3. COP as a function of vapor pressure in front of the turbine (mixture i-C4H10/R141b)

The mixture vapor pressure in front of the turbine in the range of 4500 to 5500 kPa corresponded to maximum COP values. Similar results were obtained for the mixture R600a/R161. The results of studying the effect of the geothermal fluid temperature on COP conversion ratio and the specific electric power being generated depending upon the working medium being used are given in Figures 4 and 5.

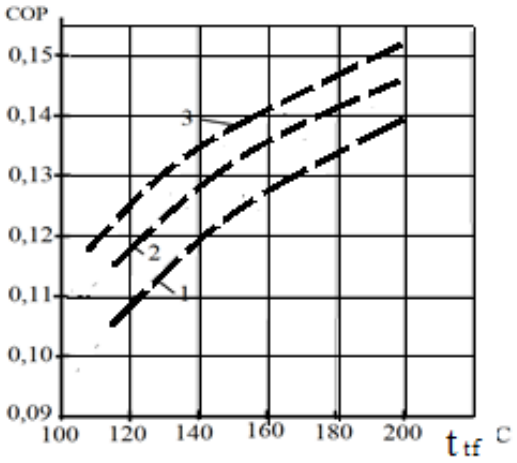


Figure 4. COP as a function of thermal fluid temperature (1-Δtmin=10K; 2-Δtmin=5K; 3-Δtmin=3K)

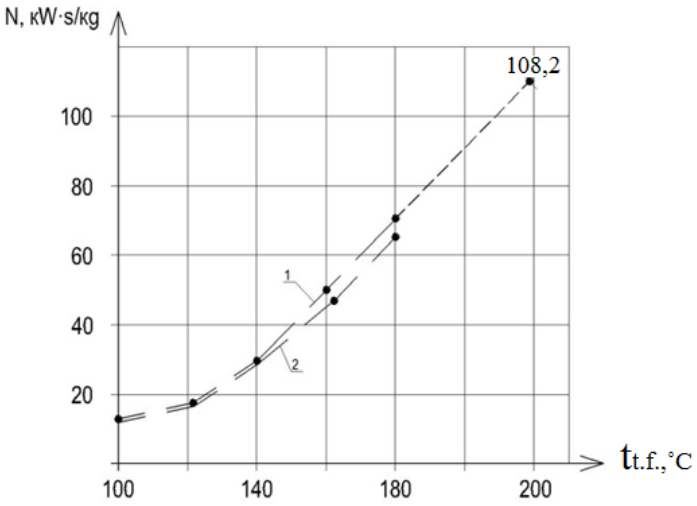


Figure 5. Electrical power being generated in the binary cycle as a function of thermal-fluid temperature. 1- isobutane [2]; 2 – isobutane/isopentane (90%) [1]) ; x- R600a/R161, Pт=6,0 MPa, supercritical cycle [authors'. data]

The results from the calculations show that the thermal fluid temperature influences the COP of geothermal power stations significantly. When there is a decrease in the temperature from 200°C to 120°C, the COP of the unit decreases from 0.145 to 0.118 (Δt_{min}=5˚C), which is equivalent to 18.6%.

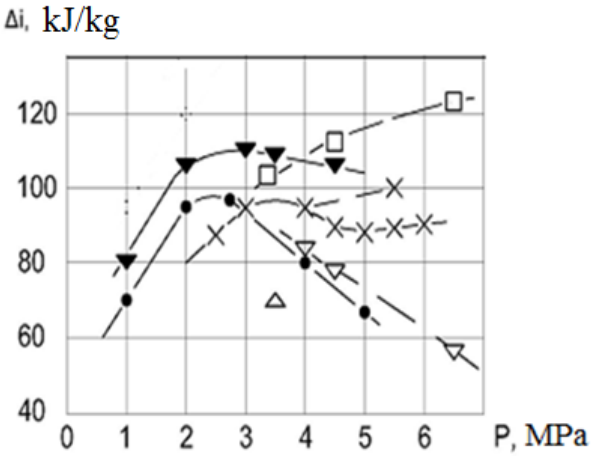


Figure 6. The operation of vapor expansion in the turbine as a function of pressure and temperature. ●- n-pentane, t = 2000C; △- n-pentane, t = 2000C; ▽ - n-pentane, t = 2200C; ▼ - n-pentane, t = 2200C; × - mixture (i-butane + R141b(60/40)), t = 2000C.

The dependence of the specific vapor expansion operation in the turbine (Δi, kJ/kg), as well as the electric power being generated (Nv, kW), on the vapor pressure in front of the turbine is more complex when the temperature is lower than the critical pressure. An increase in pressure (up to critical) results in Δi decrease (as well as Nv). When the vapor parameters are close to critical, Δi and Nv both decrease. Moreover, when the values are larger than the supercritical temperature, the pressure increase results in a Δi (Nv) increase. The comparison of cycles according to different parameters and cycle configuration are shown in Table 3.

Table 3. Cycle comparison using the conversion coefficient value. Note: * - supercritical cycles; η_t – the thermal efficiency , η_{tr} , η_k - the efficiency of triangle cycle and Karno cycle, respectively.

Working medium	η_t	η_{tr}	η_k	$\frac{\eta_t}{\eta_{tr}}$	$\frac{\eta_t}{\eta_k}$
i-C_4H_{10}/R161 (80/20)	0,14*	0,21	0,37	0,66	0,38
i-бутан/ i-pentane (90/10)	0,13	-	0,37	-	0,35
i-C_4H_{10}/R141b (60/40)	0,15*	0,21	0,37	0,71	0,40
i-C_4H_{10}/R141b (60/40)	0,155*	0,21	0,37	0,73	0,42

One of the values characterizing the heat conversion efficiency is the value of the specific working medium volume at the turbine outlet. A large volume of the working medium influences the steam turbine construction negatively, reduces the power generated, and makes the design more complex. Table 4 shows the results of numerical studies on the specific volume values in the working GeoPS cycle with the temperature of the thermal fluid being 200˚C.

Table 4. The value of specific operation by volume when using different working mediums

Working medium	$P_т$, kPa	$P_к$, kPa	Specific volume/density m^3/kg	Specific operation by volume, kJ/m^3	Ratio $\Delta l_{NH3}/\Delta l$
ammonia (NH_3)	9500	1080	0,1237/8,080	1955	1,0
i-C_4H_{10}/R161	6000	400	0,1341/7,455	755,2	2,59
i-C_4H_{10}/R161	6000	280	0,1656/6,0384	580,3	3,37
i-butane/ i-pentane	3400	270	0,2027/4,9320	497,9	3,93

The efficiency of the working medium is also determined by the value of the total flow exergy in front of the turbine. The ratio of the maximum specific theoretical power versus the exergetical power is determined according to this equation:

$$e = i(P,T) - i_0(P_0,T_0) - T_0\left[S(P,T) - S_0(P_0,T_0)\right], \quad (3)$$

where, i and S are the enthalpy and entropy of the working medium at the value of (P,T) in front of turbine; i_0 and S_0 are the enthalpy and entropy of the working medium at the parameters of the ambient air.

Total exergy is determined by the equation below:

$$E = m \cdot e \quad (4)$$

As a result of the calculations made, it was found that decreasing the temperature of the working medium vapor in front of the turbine decreases the total exergy. Thus, for the mixture R600a/R161 in the supercritical cycle, the total exergy decreases from 3702.3 kW at T=150 ºC, which is equivalent to 28 %. In the subcritical cycle with the working medium R600a/R141b, the exergy decreases from 1414.5 kW at T=200 ºC up to the value E=881,2 kW at T=140 °C, which is equivalent to 37%. The total exergy

values for mixtures R600a/R161, R600a/R141b, and R600a/n-hexane in supercritical cycles at 197 °C vary from 3702.3 to 2885.8 kW. Thus these provide high generation values for electrical power. The results of calculations for cycle efficiency with different working mediums are illustrated in Figure 7.

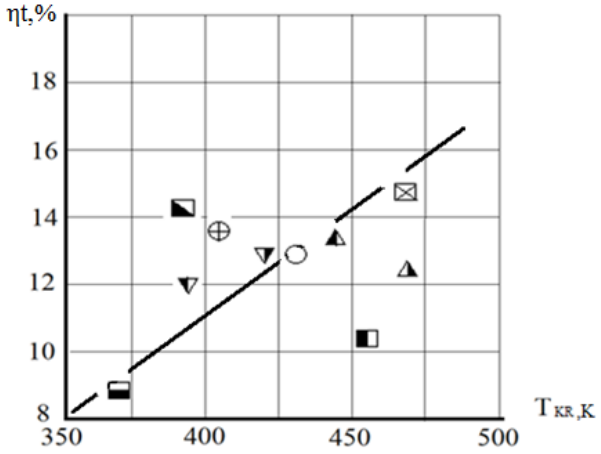


Figure 7. COP as a function of critical temperature of the working medium. - i-C4H10/R161; - R141в ; - i-C4H10/R161 (60/40); - i-butane/ i-pentane (90/10); - i-butane/ n-pentane (40/60); - n-butane (n-C4H10); - i-pentane; - i-butane/ n-hexane (40/60); - R602+R161 (50/50); - NH3+ C2H6 (60/40)

4. CONCLUSIONS

The results of numerical studies on the effect of thermodynamic and physical properties of working mediums on the efficiency of converting geothermal energy into electricity generation showed that i-C4H10/ R161 and i-C4H10/R141b mixtures provide higher power generation values in the supercritical cycle which could be used in the temperature range of 120 to 200 C.

REFERENCES

Alhasov, A.B.: Geothermal power engineering problems, resources, technologies, Moscow, 1, (2008).

Artemenko, S.V., Nikitin, D.N.: Choice of working mediums for low temperature Renkin cycles by using organic substances. II. Fluorinated esters, Cryogenic technique and technology, (2010), 6 – 10.

Bileka, B.D.: Peculiarities of initial-parameter choice of waterless Renkin cycle for power plants utilizing waste heat of drive-gas turbine units of compressor stations, Engine construction vestnik, (2011), 138 – 140.

Buholdin, Yu. S., Severin, A.S., Tatarinov, V.M., Shanov, S.V.: The increase of delivery-gas-pipe compressor station efficiency and reliability, Technological gases, (2010), 60 – 65.

Di Pippo, R.: Geothermal Power Plants: Principles, Applications and Case Studies, Oxford OX516B, UK (2005).

Redko, A.A.: Methods of increasing the efficiency of geothermal-heat supply systems, Makeevka (2010).

Redko, A.A.: Rational thermodynamical cycle parameters of the geothermal multistage station, Machine-building problems, (2010), 76 – 82.

Redko, A.: Rational Thermo-Dynamic Parameters Of Cycles Of A Multi-Stage Geothermal Power Station, 37th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, CA (2012).

Shubenko A.L.,.Malyarenko V.A, Senetskiy A.V., Babak N.Yu: Cohenerational Technologies Based on Using Low-capacity Steam Turbines in the Power Engineering. Ukraine NAS Machine Building Problem Institute, Kharkov (2014), 320p.

Pyatnychko, V.A.: Utilization of low-potential heat in the power plants with organic heat-carriers, Ecotechnologies and resources saving, 2, (2002), 10 – 14.

Zysin, V.A.: Combined steam and gas plants and cycles, Moscow (1962).