SUBCRITICAL ORGANIC RANKINE CYCLE BASED GEOTHERMAL POWER PLANT THERMODYNAMIC AND ECONOMIC ANALYSIS

by

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Original scientific paper
https://doi.org/10.2298/TSCI180104275M

This paper is focused both on the thermodynamic and economic analysis of an organic Rankine cycle (ORC) based geothermal power plant. The analysis is applied to a case study of the geothermal field Recica near the city of Karlovac. Simple cycle configuration of the ORC was applied. Thermodynamic and economic performance of an ORC geothermal system using 8 working fluids: R134a, isobutane, R245fa, R601, R601a, R290, R1234yf, and R1234ze(E)], with different critical temperatures are analyzed. The thermodynamic analysis is performed on the basis of the analysis of influence of the operation conditions, such as evaporation and condensation temperatures and pressures, and evaporator and condenser pinch point temperature difference, on the cycle characteristics such as net power output, and plant irreversibility. The economic analysis is performed on the basis of relationship between the net power output and the total cost of equipment used in the ORC. Mathematical models are defined for proposed organic Rankine geothermal power plant, and the analysis is performed by using the software package engineering equation solver. The analysis reveals that the working fluids, n-pentane and isopentane, show the best economic performances, regardless the evaporation temperatures, while the working fluid R1234yf and R290 have the best thermodynamic performances. In addition, each analyzed working fluid has its corresponding economically optimal condensation temperature (and condensation pressure). Economically optimal pinch point temperature difference of evaporator has different values, depending on the working fluid, while pinch point temperature difference of condenser has similar values for all analyzed working fluids. Analysis results demonstrate that the subcritical ORC geothermal power plant represents a promising option for electricity production application.

Key words: *ORC, geothermal power generation, thermodynamic analysis, economic analysis*

Introduction

Organic Rankine cycle plants allow the production of electricity from low-temperature geothermal sources. About 70% of the world's geothermal energy potential [1] can be included in to low moderate-temperature water-dominated systems with temperatures below 130 °C. In scientific literature [2] the ORC power plants for the exploitation of geothermal sources with temperatures below 130 °C are extensively analyzed. In the binary pow-

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er plants, the heat of the geothermal water is transferred to a secondary working fluid. Two different systems are currently in use in binary power plants, ORC and the Kalina cycle. The thermodynamically used geothermal water is then returned to the ground by the reinjection well, in order to recharge the underground water reservoir [3]. Binary power plants allowed the exploitation of a large number of geothermal fields which would be difficult (or less cost-effective) to exploit using other energy conversion technologies [4].

As a result of extensive oil and gas exploration, significant geothermal potential has been discovered in the Republic of Croatia [5]. There are several geothermal sources with geothermal water temperatures in the range from 90 °C to 175 °C. The possibilities of electricity generation from these geothermal fields have recently been considered [6].

Geothermal field Recica is situated approximately 8 km northeast of town Karlovac and was discovered in 1983 by Ka-2 well [7]. Later, during 1988, Ka-3 well was drilled which confirmed the geothermal potential of this locality. The distance between Ka-2 and Ka-3 wells is approximately 3 km. For the analysis purposes of this case study geothermal field Recica mass-flow rate 94.38 kg/s and geothermal water temperature 120 °C are assumed [8]. According to geological data obtained from the wells, two different deposits of water-saturated complexes were separated. The clastic deposits represent sandstones, marl and silt, and below them a complex of carbonate deposits constructed by dolomite, limestone and dolomite breccia. The Ka-2 exploration well has reached a final depth of 4145 m. The complex of carbonate deposits in the Ka-2 well is beneath the clastic deposits, saturated with water whose salinity is less than 1 g NaCl/L, corresponding to fresh water. The geothermal potential of this complex could be significant because it is deposits that are largely discontinued with tectonic activities and large spreads and thicknesses. The Ka-3 well reached a final depth of 3523 m. The saturation of the carbonate water reservoir, as well as the Ka-2 well, was confirmed. The borehole is a complex of clastic deposits of tertiary age, and below are thick complex of carbonate deposits. The results of mining activities in the geothermal water exploration area Recica, where Ka-2 and Ka-3 wells were situated, point to perspective of geothermal water exploitation areas.

Main ORC cycle operation conditions are evaporation and condensation temperatures and pressures, as well as evaporator and condenser pinch point temperature differences. Evaporation and condensation temperatures are the two most significant process parameters and have an important impact on the ORC cycle performance. Both temperatures are restricted, evaporation temperature by the critical temperature of the organic working fluid, and condensation temperature by the ambient temperature, respectively. The economic cost of the ORC geothermal power plant consists of the costs of individual equipment, especially heat exchangers (preheater, evaporator and condenser). The costs of the heat exchangers depend not only on the size of their surface, but also on the type of implemented materials and on the operating pressure. Changing the evaporation and condensing temperatures means changing the working pressure in the evaporator and the condenser, which affects the cost of these heat exchangers. Pinch point temperature difference has a significant impact on the size of the heat exchanger surface, and thus on its cost. In general, the area of the heat exchanger decreases with the increase of the pinch point temperature difference at the same heat transfer flux.

The most important goal of this paper is to analyze the main ORC cycle operation conditions (evaporator and condensation temperatures and pressures, and evaporator and condenser pinch point temperature differences) for selected working fluid, based on the thermodynamic and the economic criteria, and compare the obtained results. Appropriate conclusions are derived based on the analysis results.

Special attention is paid to the analysis of what influence the evaporation and condensation pressures have on the ORC thermodynamic and economic characteristics, since the pressure value significantly affects the price of the heat exchanger (evaporator and condenser).

One of the goals of this paper is to investigate the assumption that there exists an economically optimal value of evaporator and condenser pinch point temperature difference for the given environmental conditions (geothermal source and ambient air).

Thermodynamic model

Simple ORC configuration was selected for geothermal power plant, which is shown in fig. 1(a). Standard adiabatic models of the components and First and Second law balance equations are used in the thermodynamic study of the ORC.

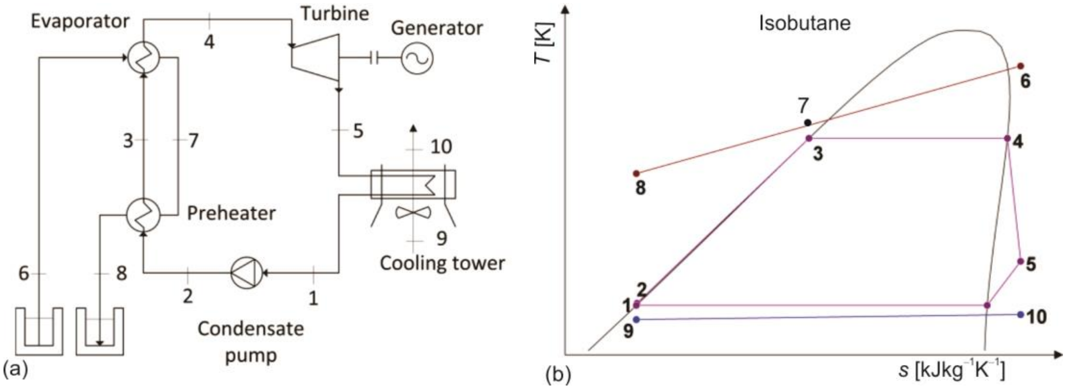


Figure 1. Schematic layout of; (a) simple ORC cycle plant and (b) the associated *T-s* diagram

Mass and energy balances for ORC power plant components at steady-state are:

$$\sum \dot{m}_{\text{in}} = \sum \dot{m}_{\text{out}} \tag{1}$$

$$\dot{Q} + \dot{W} = \sum \dot{m}_{\text{out}} h_{\text{out}} - \sum \dot{m}_{\text{in}} h_{\text{in}} \tag{2}$$

where the subscripts in and out represent the inlet and outlet states, $\dot{Q}$ and $\dot{W}$ are the net heat and work inputs, respectively, $\dot{m}$ – the mass-flow, and h – the specific enthalpy. Exergy balance for ORC power plant component is given by:

$$\dot{E}_{x_{\text{heat}}} - \dot{W} + \sum \dot{m}_{\text{in}} e_{x_{\text{in}}} - \sum \dot{m}_{\text{out}} e_{x_{\text{out}}} = \dot{I} \tag{3}$$

where e_x represents specific flow exergy and I represents irreversibility. Useful work of the ORC power plant, $\dot{W}_{\text{net}}$, is turbine work diminished for the own plant consumption. Exergy destroyed in the cycle and the plant, or the irreversibility in the cycle and the plant, are given by [9, 10] expressions:

$$\dot{I}_{\text{cycle}} = \sum \text{all components } \dot{I}_{\text{i}} = \dot{I}_{\text{p}} + \dot{I}_{\text{ph}} + \dot{I}_{\text{ev}} + \dot{I}_{\text{t}} + \dot{I}_{\text{c}} \tag{4}$$

$$\dot{I}_{\text{plant}} = \dot{I}_{\text{cycle}} + \dot{I}_{\text{rej}} + \dot{I}_{\text{acs}} = \dot{E}_{x_{\text{in}}} - \dot{W}_{\text{net}} \tag{5}$$

where the subscripts p, t, c, ph, ev, rej, and acs represent the pump, turbine, condenser, preheater, evaporator, reinjection, and air cooling system, respectively.

Energetic $\eta_{\rm en}^{\rm plant}$ and exergetic $\eta_{\rm ex}^{\rm plant}$ plant efficiencies tell how efficient the heat source is used [9], and both are defined, respectively:

$$\eta_I = \eta_{\rm en}^{\rm plant} = \frac{\dot{W}_{\rm net}}{\dot{Q}_{\rm av}} = \frac{\dot{W}_{\rm net}}{\dot{m}_{\rm geo}(h_{\rm in}^{\rm geo} - h_{\rm o}^{\rm geo})} \tag{6}$$

$$\eta_{II} = \eta_{\rm ex}^{\rm plant} = \frac{\dot{W}_{\rm net}}{\dot{E}_{x_{\rm av}}} = \frac{\dot{W}_{\rm net}}{\dot{m}_{\rm geo} e_{x_{\rm in}^{\rm geo}}} \tag{7}$$

The $\dot{Q}_{\rm av}$ and $\dot{E}x_{\rm av}$ are the heat and exergy available in the heat source, and subscript geo means geothermal brine, respectively.

When geothermal brine is used to generate electricity, the thermodynamic goal is to maximize the network output $\dot{W}_{\rm net}$. Therefore, the $\dot{W}_{\rm net}$ should be maximized. From eqs. (6) and (7) it can be concluded that this is the same as maximizing the energetic or exergetic plant efficiency, because $h_{\rm in}^{\rm geo}$, $h_{\rm o}^{\rm geo}$, and $ex_{\rm in}^{\rm geo}$ only depend on the geothermal source and the surroundings.

Working fluid selection process

The working fluids analyzed in this paper are n-pentane, isopentane, isobutane, R245fa, and R134a. These fluids are chosen because they are used in similar, already existing ORC geothermal power plants [1, 3]. Three more working fluids were selected because of their critical temperature and critical pressure values. These working fluids are R1234yf, R290 (propane), and R1234ze(E). Recent research has determined [10] that thermodynamic suitable working fluids have critical temperature lower than the inlet geothermal fluid temperature (about 18 °C). Similar results have been shown in other research papers [11], where it was found that the difference between the input temperature of the geothermal fluid and the critical point of the working fluid. Table 1 contains a list of some important properties for each analyzed working fluid. Toxicity and flammability are two very important factors regarding human safety. According to ASHRAE standard 34 [12] the letter A refers to *lowe*r toxicity while the letter B means higher toxicity. The numbers 1, 2, and 3 refer to flame propagation, where number 1 means no flame propagation, number 2 means lower flammability and number 3 means higher flammability. Moreover, the working fluid should be stable and it should not dissociate at the high pressures and temperatures in the ORC cycle. Ozone depletion potential (ODP), global warming potential (GWP) and the atmospheric lifetime (ALT) are three important factors that should be regarded as the environmental effects on the working fluids. For both safety and environmental issues, all eight considered fluids are feasible for utilization. In the last column of tab. 1 there are ΔT values, which show the difference between the input temperature of the geothermal fluid and the critical point of the working fluid.

Generally, the working fluids used in ORC cycles are categorized in three groups based on their slope of saturation vapor curves in *T-s* diagram. Fluids having positive slope are dry fluids and those having negative slope are wet, while isentropic fluids have infinitely large slopes. Dry and the isentropic fluids are the most preferred working fluids for the ORC cycles. In ORC cycles with wet fluid as a working fluid superheating is essential in order to keep the expansion in vapor phase and to prevent wet expansion and erosion in the turbine. In ORC cycles that use dry or isentropic fluid dry expansion in turbine is possible and no or low superheat is practical [13]. There are several benefits of avoiding superheating in ORC cycles especially when wet and isentropic working fluids are used [14]. In this paper it is assumed that there is no superheating of the working fluid, meaning that the working fluid has the same temperature and pressure in the evaporator and at the turbine inlet.

Table 1. Important basic properties for each analyzed working fluid

Working fluid	Critical temperature [°C]	Critical pressure [kPa]	Type of fluid	ALT (year)	ASHRAE 34 safety group	GWP	ODP	ΔT [°C]
n-pentane R601	196.5	3364	Dry	n.a.	A3	20	0	−76.5
R134a	101	4059	Isentropic	14.6 years	A1	1430	0	19.0
R245fa	154.1	3651	Isentropic	7.6 years	B1	1030	0	−24.1
Isopentane R601a	187.2	3370	Dry	12	A3	4	0	−67.2
Isobutane	134.7	3640	Wet	< 1 year	A3	3.3	0	−14.7
R1234yf	94.7	3382	Dry	0.029	A2L	4	0	25.3
R290 (propane)	96.67	4250	Wet	< 1 year 0.041	A3	20	0	23.3
R1234ze(E)	109.4	3636	Dry	< 1 year 0.045	A2L	6	0	10.6

Equipment sizing

For a precise determination of the economic cost of the ORC geothermal power plant it is necessary to implement accurate sizing of individual equipment, especially heat exchangers. Preheater and evaporator are assumed to be horizontal shell and tube counter flow heat exchangers. Considered are only single tube pass and shell pass heat exchangers with square pitch tube layout. Preheater and evaporator use tubes with 19.06 mm inner diameter, while it is assumed that the outer diameter of the pipes is 20% wider and the tube pitch is 1.5 times wider than the outer diameter. In the condenser there are built-in tubes with 6.35 mm inner diameter. In preheater fluids are exchanging heat in single-phase flow, whereas in evaporator and condenser in two-phase flows. In preheater and the evaporator working fluid-flows through the tubes and the geothermal fluid-flows through the shell side. Condenser is assumed to be a plate-fin-and-tube heat exchanger, where ambient air is cooling the working fluid.

All transport properties of a working fluid, for example thermal conductivity, k, and the Prandtl number, do not remain constant during the heat exchange process in the ORC cycle because of temperature variations. With a goal to decrease the influence of temperature variations on the transport properties during heat transfer evaluation, each part of heat exchangers (preheater, evaporator and condenser) is divided into equal sections. The methodology used to discretize the heat exchangers was developed according to Nellis and Klein [15]. The heat exchangers are divided into N sub-heat exchangers with equal changes in the temperature of each of the working fluid. In this way all input and output temperatures are known for each N sub-heat exchanger, and precise mean values of fluid transport properties can be determined for each N sub-heat exchanger. Log mean temperature difference method is applied for each sub-heat exchanger, and its surface, A_j, can be calculated.

Correlations used for calculation of the tube side and the shell side heat transfer coefficients for each heat exchanger are listed in tab. 2. Total heat transfer area, A_{tot}, for each heat exchanger is calculated by summing all surfaces of the N sub-exchangers. Deviations in value of the A_{tot}, which are mainly affected by transport properties of the working fluids, are particularly pronounced with smaller number of the N sub-exchangers. In this study, to decline the influence of temperature variations on the transport properties during heat transfer evaluation, the number of sections (sub-exchangers) in the preheater, N_{ph}, evaporator, N_{ev}, and condenser, N_{con}, are selected to be N_{ph} = 30, N_{ev} = 40, and N_{con} = 300, respectively.

Table 2. Correlations used for calculation of the tube side and the shell side heat transfer coefficients and pressure drop in heat exchangers

Heat exchanger	Heat transfer coefficient model (tube side)	Ref.	Heat transfer coefficient model (shell side)	Ref.	Pressure drop correlation (tube side)	Ref.	Pressure drop correlation (shell side)	Ref.
Preheater (single phase)	Gnielinski correlation	[16, 17]	Kern, Kakac and Lin	[18, 19]	Kern, Kern and Kraus	[18, 20]	Kern, Kern and Kraus	[18, 20]
Evaporator (evaporation)	Gungor and Winterton	[21, 22]	Kern, Kakac and Lin	[18, 19]	Kern and Kraus	[18, 20]	Kern, Kern and Kraus	[18, 20]
Air cooling condenser (condensation)	Shah	[23]	Ganguli *et al.* (air side)	[24]	Kern, Kern and Kraus, Steiner correl., Friedel correl.	[18, 20, 25, 26]	Air side pressure drop	[27-29]

The determination of pump power and air condenser fan power was performed by calculating pressure drop in shell and tube side of the heat exchangers. Correlations used for calculation of the tube side and the shell side pressure drop in heat exchangers are listed in tab. 2.

Economic model

Module costing technique (MCT) was used to perform the economic analysis of the ORC plant, which is commonly used for preliminary cost estimates of chemical plants [30]. This costing technique is based on determination of purchased cost of equipment evaluated for some base conditions, C_P^o. The cost equations have the following expression:

$$\log_{10} C_\mathrm{P}^\mathrm{o} = K_1 + K_2 \log_{10}(Y) + K_3 \left[\log_{10}(\mathrm{Y})\right]^2 \tag{8}$$

where Y is the power capacity of turbine and pump, or the heat transfer area of evaporator, pre-heater, and condenser, respectively, in the ORC system, and the constants K_1, K_2, and K_3 are peculiar to each component and type. Using multiplying factors F_P and $F_{\mathrm{M},}$ for the system pressure and materials of construction, deviations from the base conditions is taken into account. The pressure factor is given by the following general equation:

$$\log_{10} F_\mathrm{P} = C_1 + C_2 \log_{10}(P) + C_3 \left[\log_{10}(P)\right]^2 \tag{9}$$

where p is the pressure and C_1, C_2, and C_3 are coefficients peculiar to each component and type. In MCT, the bare module cost factor, F_BM, is the aggregate multiplication factor that accounts for all the direct and indirect costs:

$$C_\mathrm{BM} = C_\mathrm{P}^\mathrm{o} F_\mathrm{BM} \tag{10}$$

where C_BM, means bare module equipment cost, is the sum of the direct and indirect costs. The expression of the bare module cost factor for heat exchangers and pumps is:

$$F_\mathrm{BM} = B_1 + B_2 F_\mathrm{P} F_\mathrm{M} \tag{11}$$

where B_1 and B_2 are dependent on the type of heat exchanger or pump, and F_P and F_M account for the effects of the operating pressure and construction material on costs. For other components the coefficient F_BM is directly given as a multiplier that accounts for equipment description in terms of type, operating pressure and material.

All main assumptions and simplifications used in the application of the MCT method for ORC geothermal power plants and all coefficients used for the evaluation of the bare module equipment cost, C_{BM}, are in accordance with the reference [31]. Total cost of equipment, C_{tot}, is calculated by summing bare module equipment cost, C_{BM}, of all equipment that contains ORC geothermal power plant.

For economic performance estimation of the ORC geothermal power plant Recica net power output index (*NPI*) was used for the purposes of this analysis. The *NPI* [32] representing the ratio of the net power output, $\dot{W}_{net}$), to C_{tot}, for the ORC system is indicated:

$$NPI = \frac{\dot{W}_{net}}{C_{tot}} \tag{12}$$

Specifications for calculation and methodology of analysis and optimization

At the geothermal field Recica the amount of cooling water for the water-cooled condenser are not sufficient. Because of that fact, the air-cooled condenser is used. Thermodynamic calculations have been performed with the average annual air temperature 15 °C. For the analysis purposes of this case study mass-flow rate 94.38 kg/s and temperature 120 °C of geothermal water are assumed in thermodynamic calculations, and later in economic calculations, with special attention paid to the values of pinch points both for the evaporator and for the air-cooled condenser. The presumed turbine isentropic efficiencies are 0.85 for the ORC (dry turbine) and 0.8 for the feed pump [33].

All mathematical models are defined and analysis is performed using the software package engineering equation solver (EES) [34]. Some transport properties of working fluids are determined using CoolProp software.

Thermodynamic parametric analysis is based on solving thermodynamic mathematical model of the ORC geothermal power plant run with different selected working fluids, which are listed in tab. 1. The thermodynamic parametric analysis was performed using variation of evaporation temperature, T_E, (or turbine inlet temperature) and evaporation pressure, P_E, on selected parameters. Selected parameters are $\dot{W}_{net}$ and plant irreversibility, $\dot{I}_{plant}$. Optimal thermodynamic operating conditions were selected, corresponding to the maximum $\dot{W}_{net}$ and the minimum overall $\dot{I}_{plant}$. In this way, the thermodynamic optimum value of evaporation temperature T_E (or turbine inlet temperature) and evaporation pressure P_E is determined.

The economic optimization consists of searching for the maximum value of an objective function subject to constraints imposed by the equations of the ORC geothermal power plant model. Objectives function being considered is *NPI*. In the search for the optimum (maximum) *NPI*, P_E and the condensation pressure, P_C, are chosen as optimization variables. Optimization is performed using the EES optimization algorithm. Conjugate directions method or Powell's method was used for mathematical optimization purposes. The basic idea of this method is to use a series of 1-D searches to locate the optimum. The optimization results obtained by this method were validated using economic parametric analysis.

Economic parametric analysis is based on solving thermodynamic mathematical model of the ORC geothermal power plant, simultaneously with the economic model and equipment sizing model, for all selected working fluids. The effects of variation of T_E (or turbine inlet temperature) and P_E on *NPI* were analyzed. Optimal economic operating conditions, corresponding to optimal economic evaporation temperature, $T_{E,opt}$, (or turbine inlet temperature) and optimal economic evaporation pressure, $P_{E,opt}$, where *NPI* has maximum value, NPI_{max}, were determined. Afterwards, the analysis of variation condensation temperature, T_C, and P_C on NPI was carried out. In this way, the optimal economic condensation temperature, $T_{C,opt}$, and optimal economic pressure, $P_{E,opt}$, were determined.

The performance of heat transfer in heat exchangers in ORC geothermal power plant depends significantly on the temperature difference between geothermal heat source and working fluid in preheater and evaporator and on the temperature difference between cooling ambient air and working fluid in condenser. The higher temperature difference of the heat source in the heat exchanger and heat sink enhances the heat transfer rate and has a favorable result for the investment cost. But, at the same time, this means that the lower temperature of evaporation has occurred in the evaporator and the higher temperature of condensation in condenser, which has the effect of lowering the turbine power output. To analyze this conflicting situation, pinch point temperature difference in evaporator, ΔT_{pp}, is employed to evaluate the economic performance of the heating process in the ORC system, since ΔT_{pp} represents the gap of temperature difference between geothermal source and the working fluid in the evaporator. On the other side, pinch point temperature difference in condenser, ΔT_{cond}, is applied for cooling process, since ΔT_{cond} indicates the gap of temperature difference between the working fluid and the cooling air in the condenser.

The economic analysis was carried out by maximizing NPI using the optimal economic evaporation temperature and pressure, and the economic optimal condensation temperature and pressure for each working fluid. The ΔT_{pp} and ΔT_{cond} are chosen as free variables. The analysis results obtained by optimization were validated using economic parametric analysis.

Results and analysis

This section demonstrates the results of the thermodynamic and economic parametric analysis and the economic analysis for the selected working fluids in the ORC geothermal power plant Recica. The effects of T_E and P_E, T_C and P_C, ΔT_{pp}, and ΔT_{cond}, on $\dot{W}_{net}$, $\dot{I}_{plant}$ and NPI were analyzed.

The working fluids used in the thermodynamic and economic analysis and the optimization are given in tab. 1. Four of the working fluids have a critical temperature lower than the initial geothermal fluid temperature (120 °C). These working fluids are R1234yf, R290, R134a and R1234ze(E). In last column of tab. 1 there are values of the ΔT, which represents the difference between the input temperature of the geothermal fluid and the critical point of the working fluid. Thus, these working fluids have a positive value of ΔT, whose value decreases from the first to the last (fourth) working fluid. The other four working fluids that are being considered have a critical temperature higher than the initial temperature of the geothermal fluid, which means their ΔT value is negative. The highest negative value of ΔT have n-pentane, isopentane, R245fa, and lastly isobutane.

The optimal economic values for the turbine inlet, P_E,and outlet pressure, P_C, where NPI_{max} is achieved, are evaluated and listed in tab. 3. for selected working fluids.

Figure 2 displays the effects of T_E (a) and P_E (b) on $\dot{W}_{net}$, $\dot{I}_{plant}$ and NPI for analyzed working fluids. By analyzing the mode of change of $\dot{W}_{net}$ with T_E and P_E in fig. 2, it can be concluded that the working fluids can be divided into two groups. The first group consists of working fluids with the highest values of factor ΔT, namely R1234yf and R290. In case this group of working fluids is used, by increasing the value of T_E or P_E, there is a continuous increase of $\dot{W}_{net}$. Moreover, there is no maximum value of the $\dot{W}_{net}$, thus it can be assumed that the optimum thermodynamic T_E value is 10 °C lower than the critical temperature (for practical and safety reasons), which determines the value of the optimal thermodynamic P_E

Table 3. Optimal values for the thermodynamic and economic analysis and optimization for selected working fluids

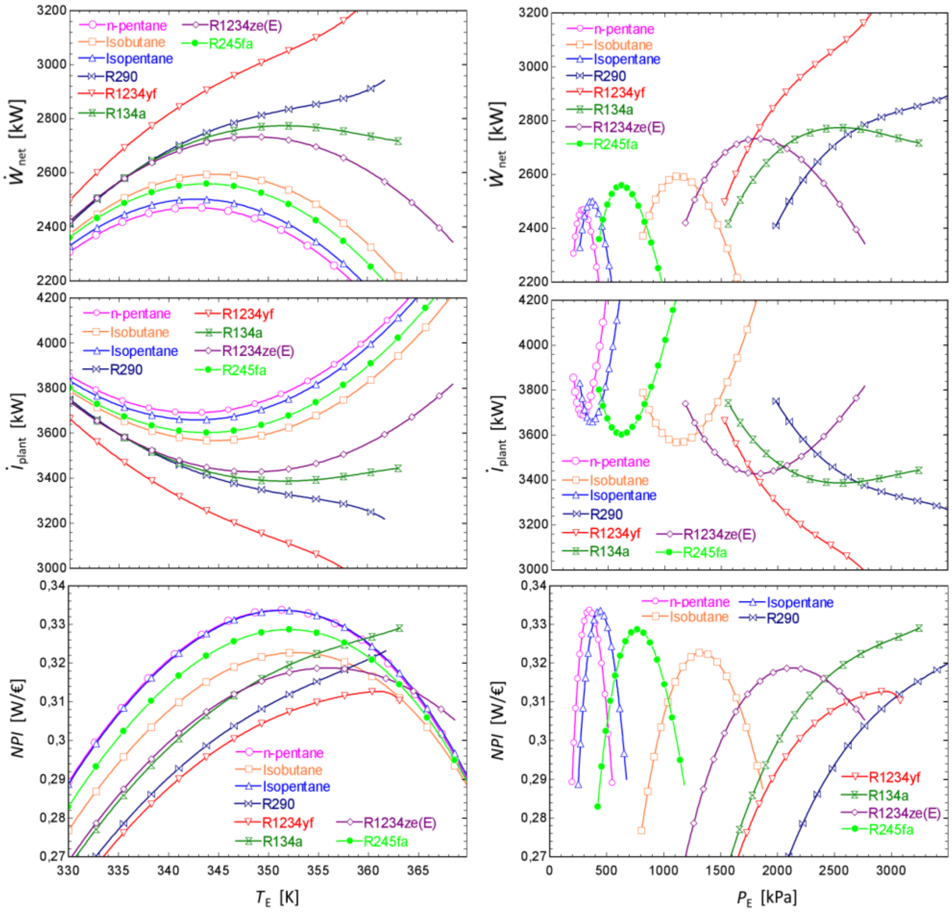
Fluid		n-pentane	Isobutane	Isopentane	R290	R1234yf	R134a	R1234ze(E)	R245fa
Thermo dynamic	T_E [K]	342.5	345	343.2	359.82	357.7	352	348	344.2
	P_E [kPa]	278.3	1,131	356.3	3,545	2,772	2,517	1,295	627.1
	$\dot{W}_{net}$ [kW]	2,471	2,595	2,502	2,899	3,159	2,777	2,735	2,550
	$\dot{I}_{plant}$ [kW]	3,685	3,565	3,658	3,255	3,020	3,382	3,433	3,598
Economic	T_E [K]	350.7	351.9	353.3	352	363	363.1	360.8	360.7
	P_E [kPa]	344.9	1,309	458.4	3,063	3,074	3,242	2,358	951.7
	T_C [K]	293.7	293.8	293.7	294.2	294.4	293.9	293.7	293.4
	P_C [kPa]	58.2	307.7	78.16	860.3	613.9	585.7	437	123.7
	ΔT_{pp} [K]	2	2	2	5.2	6.8	2	2	2
	ΔT_{cond} [K]	4.18	4.2	4.3	4.3	4.4	4.2	4.1	4.1
	$\dot{W}_{net}$ [kW]	2,543	2,551	2,397	2,728	3,062	2,708	2,604	2,263
	NPI [W/€]	0.3361	0.3244	0.3375	0.316	0.3248	0.3298	0.3175	0.3229

[35]. These working fluids achieve the highest values of $\dot{W}_{net}$, meaning that they have the best thermodynamic performances. Some lesser thermodynamic performance is achieved by working fluids R134a and R1234ze(E). With these working fluids $\dot{W}_{net}$ continuously increases with the rise of T_E, until it reaches the maximum value $\dot{W}_{net,max}$, and then begins to steadily fall. The third group of working fluids comprises isobutane, R245fa, isopentane and n-pentane. This group demonstrated nearly similar change $\dot{W}_{net}$ with T_E variation. With increasing T_E, the values of $\dot{W}_{net}$ first increase, and then reach maximum, and finally decline. The maximum $\dot{W}_{net}$ values are significantly lower when compared with other working fluids. For all these working fluids optimal thermodynamic T_E is from 69 °C to 72 °C. From fig. 2 it can be concluded that those working fluids which achieve higher values of maximum $\dot{W}_{net}$, also achieve it at higher values of P_E. All selected operating fluids achieve minimum $\dot{I}_{plant}$ values at the same evaporation temperature and pressure at which maximum $\dot{W}_{net}$ are achieved. All optimal thermodynamic values (T_E, P_E, $\dot{W}_{net}$ and $\dot{I}_{plant}$) are listed in tab. 3.

Economic parametric analysis is performed to determine the optimal economic value of the $T_{E,opt}$ and the optimal economic value of the $P_{E,op}$ that achieves the maximum value of the *NPI*. Working fluid that achieves the highest value of *NPI* has the best economic performance for ORC geothermal power plant. Figure 2 shows that the best economic performance has working fluids isopentane and n-pentane that have critical temperatures greater than the input temperature of the geothermal fluid (that implies that a variable of the ΔT variable has negative values).

The highest values of NPI_{max} have isopentane and n-pentane which amounts 0.3375 W/€ and 0.3361 W/€, respectively. Working fluids that have reached the highest $\dot{W}_{net}$, namely R290 (ΔT = 23.3 °C) achieve the lowest NPI_{max} value. Similarly, it can be concluded for other working fluids that have achieved high $\dot{W}_{max}$ maximal values. The reason is that they have the biggest total C_{tot} of the ORC geothermal power plant, and in this way the excellent thermodynamic performance is unprofitable.

Figure 3 show the effects of T_C (a) and P_C (b) on *NPI*. As T_C and P_C (or turbine outlet pressure) increases, $\dot{W}_{net}$ decreases and $\dot{I}_{plant}$ increase for each analyzed working fluid. The lower the T_C and P_C are, the smaller the temperature difference between the working fluid



(a) (b)

Figure 2. The effect of: (a) T_E and (b) P_E on $\dot{W}_{net}$, $\dot{I}_{plant}$ and *NPI*
(*for color image see journal web site*)

and the cooling ambient air will be. From fig. 3 it is shown that the *NPI* initially rises with the increasing T_C and P_C, then reaches a maximum and finally decreases. Each analyzed working fluid has the NPI_{max} and its corresponding economic optimal T_C and P_C which are listed in tab. 3. All considered working fluids have a similar condensation temperature, with ranges from 20.25 °C to 21.25 °C. Although isopentane and n-pentane display the lowest value of economic optimal condensing pressure (0.7816 bar and 0.582 bar), they have the highest NPI_{max} values, 0.3375 W/€ and 0.3361 W/€, respectively. The highest values of the economic optimal condensation presses have R290 and R1234yf, 8.603 bar and 6.139 bar, with slightly lower of NPI_{max} values of 0.316 W/€ and 0.3248 W/€, respectively.

Figure 4 shows economic analysis results, that was carried out by maximizing the NPI_{max} using the optimal economic evaporation temperature and pressure, and optimal condensation temperature and pressure for each working fluid. The contour diagram was used to represent this data. The ΔT_{pp} and ΔT_{cond} are chosen as free variables. All economic optimal results ($\Delta T_{pp,opt}$ and $\Delta T_{cond,opt}$) are listed in tab. 3. The results obtained by optimization were validated using economic parametric analysis.

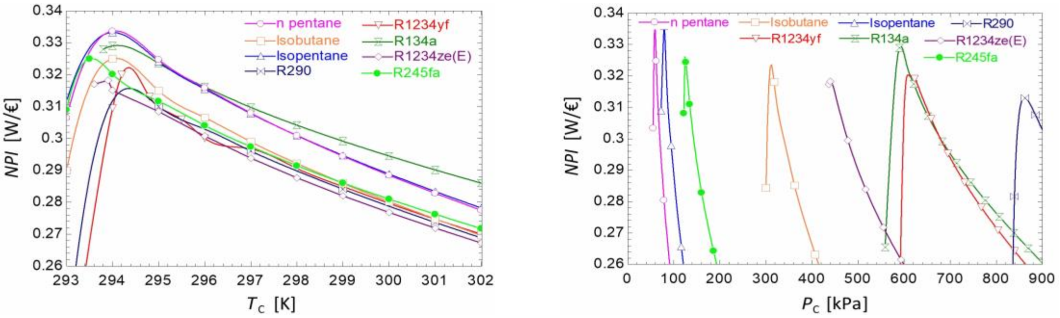


Figure 3. The effect of: T_C (a) and P_C (b) on *NPI*
(*for color image see journal web site*)

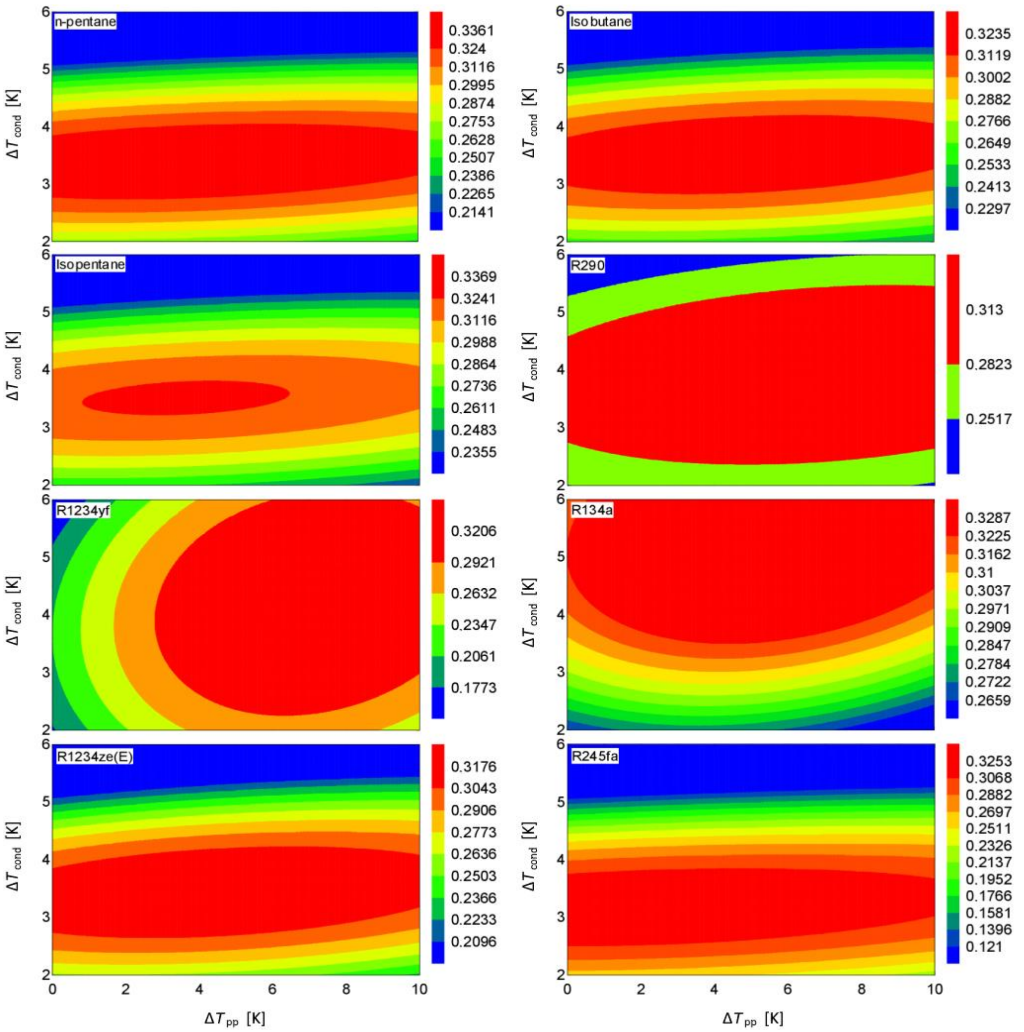
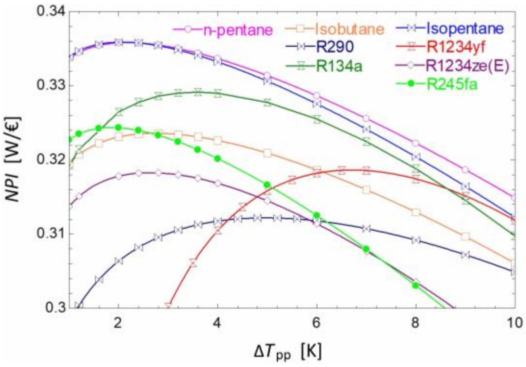


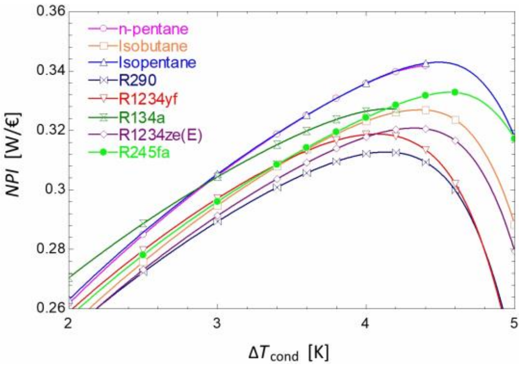
Figure 4. Contours of *NPI* as a function of ΔT_{pp} and ΔT_{cond}
(*for color image see journal web site*)

The rise of ΔT_{pp} values reduces the evaporation temperature of the ORC power plant and causes $\dot{W}_{net}$ to decrease for all working fluids. This happens because the geothermal source conditions remain unchanged, as well as the temperature in condenser. At the same time, the increase in ΔT_{pp} causes reduction of the $\dot{I}_{plant}$. The *NPI* values for all working fluids initially ascend, then obtain their maxima, and finally descend with ΔT_{pp}. Therefore, for each analyzed working fluid exists an optimal $\Delta T_{pp,opt}$ which gives maximum *NPI*. Isopentane, n-pentane, R245fa, isobutene and R1234ze(E) achieves optimal $\Delta T_{pp,opt}$ at temperature of about 2 °C. Only R1234yf (6.8 °C) and R290 (5.2 °C) gained higher value, as shown in fig. 5(a).

Figure 5(b) describes the parametric analysis results regarding the influence of ΔT_{cond} on *NPI*. As ΔT_{cond} increases, $\dot{W}_{net}$ remains constant for each working fluid in the ORC power plant. The working fluid temperature value in the condenser, T_C, was kept constant during the simulation, thus the change of ΔT_{cond} did not affect the $\dot{W}_{net}$ value. In this way, only ΔT_{cond} have influence on the economic performance of the ORC power plant. The *NPI* values for all working fluids descend initially, then obtain their minimum, and finally sharply ascend with ΔT_{cond}. As a consequence, the maximum *NPI* can be identified at the corresponding ΔT_{cond} for each working fluid. Therefore, optimal $\Delta T_{pp,opt}$ exist for each analyzed working fluid which gives maximum *NPI*. All working fluids reach the have optimal values about at 4 °C, and again, isopentane and n-pentane achieve the biggest *NPI* values.



(a)



(b)

Figure 5. The effect of ΔT_{pp} (a); and ΔT_{cond} (b) on *NPI*
(*for color image see journal web site*)

Conclusions

Both thermodynamic and economic analysis were carried out for an ORC based geothermal power plant applied to a case study of the geothermal field Recica near town Karlovac. The parameter *NPI*, representing the ratio of $\dot{W}_{net}$, to the C_{tot} of the ORC geothermal power plant, is applied to assess economically suitable working fluids and working parameters. Such parameters are T_E and P_E, T_C and P_C, ΔT_{pp} and ΔT_{cond}. The results support the following conclusions.

In the process of selecting a suitable working fluid for ORC geothermal power plant, the difference between the input temperature of the geothermal fluid and the critical temperature of the working fluid, ΔT, plays an impartment role. The working fluids whose critical temperature was significantly lower than the input temperature of the geothermal fluid (about 25 °C), achieved high values of $\dot{W}_{net,max}$ in the ORC cycle, but had modest economic performances. On the other side, working fluids whose critical temperatures are significantly higher than the input temperature of the geothermal fluid (about 65 °C to 75 °C) have achieved the highest values of $NPI_{\max}$, with relatively low values of $\dot{W}_{\text{net,max}}$.

In the case of the ORC geothermal power plant Recica (with the input temperature of the geothermal fluid is 120 °C), n-pentane and isopentane, showed the best economic performances, while the working fluid R1234yf and R290 have the best thermodynamic performances. As all of the working fluids achieved the relatively similar value of $NPI_{\max}$, so it would be useful to conduct an economic analysis with another economic indicator and compare obtained results. The acquired results confirm that the choice of the used in the ORC geothermal power plant and applied process parameters, should be both thermodynamically and economically analyzed.

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Paper submitted: January 4, 2018
Paper revised: May 10, 2018
Paper accepted: May 17, 2018