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COMBINED HEAT AND POWER PRODUCTION FROM GEOTHERMAL SOURCES USING SIMPLE SPLIT FLOW AND ADVANCED DOUBLE STAGE ORGANIC RANKINE CYCLE CONFIGURATIONS

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SUMMARY: With the rise of energy needs and decentralization of power generation, and especially the need for energy production from renewable sources, the use of power plants based on organic Rankine cycle is becoming more and more significant. However, this type of power plant wastes a lot of available heat after preheating of the working fluid. Combined heat and power (CHP) production enables mitigating wasted heat potential and increasing the overall efficiency of the organic Rankine cycle-based power plant. The aim of this work is thermodynamic characteristics determination and their comparison, for two organic Rankine cycle configurations for combined heat and power: split flow simple organic Rankine cycle (SF SORC) and double stage organic Rankine cycle (DS ORC). Considered geothermal sources are low to medium temperature sources between 120°C and 180°C. The methodology includes thermodynamic analysis and optimization of the specified organic Rankine cycle configurations for heat and power production from geothermal sources. The obtained results show that the combined heat and power split flow simple organic Rankine cycle (CHP SF SORC) configuration is superior to the combined heat and power double stage organic Rankine cycle (CHP DS ORC) configuration, where plant (system) efficiency can be increased up to 28% for low temperature district heating, and for district heating plant (system) efficiency usually increases from about 12% to 18% depending on the working fluid and the temperature of the geothermal fluid. With regard to combined heat and power double stage organic Rankine cycle (CHP DS ORC) configuration plant (system) efficiency can be increased up to 18% for low temperature district heating, and for district heating plant (system) efficiency usually increases from 5% to 8%.

Key words: *Organic Rankine Cycle, geothermal energy, combined heat and power, split flow principle, double stage*

INTRODUCTION

By searching scientific publication databases, it was determined, that in the last decade, the number of scientific publications analysing Organic Rankine Cycle (ORC) plants has increased dramatically *(Parka et al., 2018)*. Several articles published in the last few years provides a comprehensive review of the previously published research results of various aspects of ORC plants. Parka et al. *(2018)* in their paper processed a comprehensive analysis of experimental results performed on laboratory ORC plants published in more than 200 scientific papers. Most of the experimental research was carried out on micro and mini ORC plants up to 10 kW output power. Jiménez-García et al. *(2023)* provided an extensive bibliographic overview of scientific research related to ORC, and included Single-Stage, Two-Stage and Hybrid ORC plant configurations in the analysis. It was emphasized that using Two-Stage ORC configurations can achieve higher values of thermal effi-

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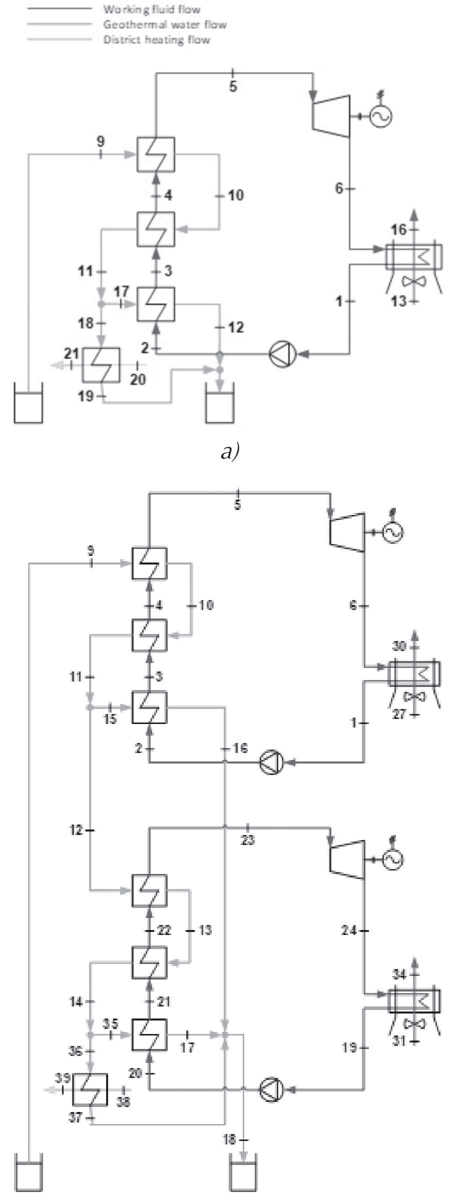
ciency and net power compared to Single-Stage ORC configurations. Several review articles have also been published that deal with the possibilities of using geothermal energy in ORC plants. Loni et al. (2021) gave an overview of the use of geothermal energy in ORC cogeneration plants for the combined production of heat and power (CHP), trigeneration plants for the combined production of cooling energy, heat and power (combined cooling, heating and power CCHP), and in polygeneration plants. Ahmadi et al. *(2020)* analysed in detail the key factors affecting the energy and energy efficiencies of ORC plants. A comparison of conventional power generation systems and various ORC configurations was carried out based on economic indexes (electricity production costs and levelized cost of electricity) with the aim of determining the commercial status of ORC plants. Life cycle assessment and environmental impact of geothermal ORC plants were also reviewed. In the review paper Haghighi et al. *(2021)* deals with previous research that is focused on modelling and optimizing the operating conditions of various ORC configurations. The conclusion after the analysis is that the performance of the geothermal ORC plant is significantly influenced by the type of selected working fluid, working condition and ORC configuration.

To meet current and future demands for heat energy from limited resources of renewable energy sources, district heating systems (DHS) play an important role in measures to increase energy efficiency. District heating systems (DHS) consists of a network of pipelines that supply thermal energy to buildings in certain urban zones, which can be of different sizes from a neighbourhood to an entire city. Thermal energy can be produced in a centralized plant, or in a number of decentralized units. The most energy-efficient way of producing thermal energy is the use of a wide range of combined heat and power (CHP) systems, especially those that use renewable energy sources. For this reason, geothermal CHP ORC plants have been extensively studied in the scientific literature. Wieland et al. *(2016)* described six state-of-the-art CHP ORC configurations. Basic CHP ORC configurations are series, parallel *(Erdeweghe et al., 2017, Heberle et al., 2010)* and series/parallel *(Habka, Ajib, 2013)*. The series/parallel CHP ORC configuration combines the good properties of the parallel configuration, which enables high supply temperatures in the DHS, and the series configuration, which allows high utilisation of the heat source. The condensing CHP ORC configuration *(Teng et al., 2021)* is suitable for high-temperature heat sources, while the series/condensing configuration combines the advantages of both individual configurations. In addition to the basic CHP ORC configurations, new configurations have been proposed in the open scientific literature *(Fiaschi et al., 2014, Habka, Ajib, 2014)*, which under certain conditions achieve better characteristics than the mentioned basic configurations.

Future sustainable energy systems will be exclusively based on renewable energy sources, among which geothermal energy plays an increasingly important role. One of the main features of future sustainable energy systems is increasing energy efficiency, where District Heating Systems will have an important role. In EU Commission strategy for competitive, sustainable and secure energy *(COM, 2010)* emphasize the need for high efficiency cogeneration, district heating and cooling systems and promotion of smart heating and cooling grids. Today's district heating (DH) systems are considered 3rd generation and will have to go through significant changes to meet the demands of low energy buildings and smart energy systems integration. Modern district heating systems are called low temperature district heating (LTDH) systems, or 4th Generation District Heating Systems (4GDH); *(Lund et al., 2014)*.

The main task of this work is to determine how much heat can be delivered to the district heating (DH) and low temperature district heating (LTDH) systems from the simple ORC (SORC) configuration with implemented geothermal fluid split flow principle (CHP SF SORC), assuming the maximum production of net power (WNET), for the geothermal heat source from between 120°C and 180°C and sixteen selected working fluids. New double stage ORC (CHP DS ORC) configuration for combined heat and power (CHP) is presented, and its DH and LTDH characteristics are compared with the SF SORC configuration. The basic DS ORC configuration consists of two SORC configurations connected in series. Braimakis and Karellas *(2018)* concluded that exergetic efficiency, for DS ORC configuration compared to SORC configuration, can be increased up to 25% depending on heat source temperature and working fluid.



a)

b)

Figure 1. Thermodynamic schemes of the proposed geothermal combined heat and power (CHP) ORC configurations: a) simple organic Rankine cycle configuration with implemented split flow principle (CHP SF SORC), and b) double stage organic Rankine cycle (CHP DS ORC) configuration

Slika 1. Termodinamičke sheme predloženih ORC konfiguracija za kombiniranu proizvodnju toplinske i električne energije (kogeneracija) iz geotermalne energije: a) konfiguracija jednostavnog Rankineovog ciklusa s organskim fluidom s razdvajanjem toka geotermalnog fluida (CHP SF SORC), i b) konfiguracija dvostupanjskog rankineovog ciklusa s organskim fluidom (CHP DS ORC)

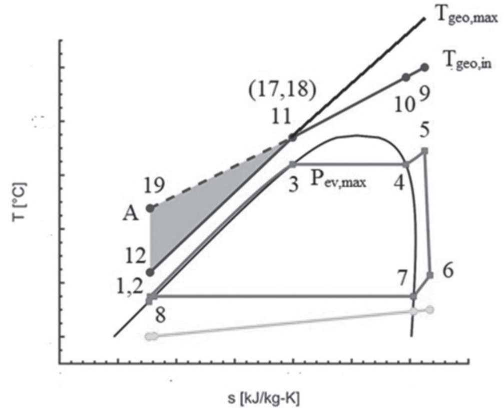


Figure 2. Representation of the simple organic Rankine Cycle (SORC) in T, s-diagram

Slika 2. Prikaz konfiguracije jednostavnog Rankineovog ciklusa s organskim fluidom (SORC) u T, s-dijagramu

METHODOLOGY

Systems Description

Thermodynamic scheme of the proposed combined heat and power simple organic Rankine cycle with split flows (CHP SF ORC) configuration are represented in Figure 1(a). Geothermal energy is used for preheat, evaporate and superheat the working fluid in the ORC plant. The produced superheated working fluid vapor goes to the turbine, where the energy taken from the working fluid is converted into mechanical work, which is converted into electrical energy in the electric generator. After the turbine, the working fluid is desuperheated, condensed and subcooled in the condenser using air in the air-cooled condenser. The subcooled working fluid goes to the pump where it is compressed to the working pressure. After the geothermal fluid transfers heat energy to the working fluid in the cycle, it is reinjected in the geothermal well.

In the proposed double stage Organic Rankine Cycle (CHP DS ORC) configuration, dual pressure evaporation strategy and high temperature stage split flow preheating strategy are applied. Application of the above strategies enables improvement of the temperature profile match between the geothermal and working fluid flow, which reduces exergy destruction in the heat transfer process Figure 1. (b).

Double stage ORC (DS ORC) configuration consists of two separate series-connected SORC plants (stages) who share a common heat source (geothermal fluid). In the first ORC plant (stage) the working fluid pressure and temperature of evaporation are higher, which is therefore called the high-temperature stage (HTS) and in the second ORC plant (stage), the temperature and pressure of evaporation are lower, so it is called low-temperature stage (LTS). The heat source (geothermal fluid) first exchanges heat flow with the working fluid in the high-temperature stage (HTS), and then with the working fluid in the low-temperature stage (LTS). After superheating and evaporation in the HTS the geothermal fluid flow is divided into two parts. The first flow is used to preheat the working fluid in the HTS, while the second flow goes to the LTS. It is desirable that the largest flow of the geothermal fluid goes to the LTS, so the minimum flow of the geofluid is used for preheating, which means that the pinch point temperature difference will move from evaporator entrance to the entrance of the HTS preheater. Pinch point temperature difference represents the place where the temperature difference between the working fluid and the geothermal fluid is the smallest. The LTS structurally have the same configuration as the simple organic Rankine cycle (SORC).

Figure 2 shows a simple organic Rankine cycle (SORC) in a T,s-diagram. With an increase of the inlet temperature of the geothermal fluid ($T_{geo,in}$) in the SORC configuration, it is possible to increase the working fluid evaporation pressure in the evaporator, which allows greater net power (W_{NET}) production. The minimum temperature difference between the geothermal fluid and the working fluid (temperature pinch point) is positioned at the entrance of the evaporator (points 3 and 11 shown in Figure 2.). Under working fluid subcritical conditions such an increase of the evaporation pressure with increasing the geothermal fluid inlet temperature ($T_{geo,in}$) can reach the maximum allowed value of the evaporation pressure ($P_{ev,max}$), which is 90% of the used working fluid critical pressure value (P_{cr}). It should be emphasized that during this process, the temperature pinch point is constantly located at the entrance to the evaporator (in our case fixed at a value of 10°C). At that value of the geothermal fluid inlet temperature ($T_{geo,in}$) (point 9 in Figure 2.), it is evident from the T,s-diagram, that the geothermal fluid outlet temperature (point A in Figure 2.) is significantly higher than the inlet temperature of the working fluid in the preheater (point 2 Figure 2.). Thus, once the maximal evaporation pressure ($P_{ev,max}$) is fixed, so with a further geothermal fluid inlet temperature ($T_{geo,in}$) increase an additional amount of heat can be absorbed only by further increasing the mass flow of the working fluid in the cycle, which results in an increase in the slope of the temperature profile of the geothermal fluid. Therefore, the geothermal fluid outlet temperature further decreases, and approaches the value of the inlet temperature of the working fluid in the preheater. At a certain value $T_{geo,in}$, the outlet temperature of the geofluid achieves a minimal temperature difference (for example 9°C) with the inlet temperature of the working fluid in the preheater (points 2 and 12 shown in Figure 2.), which means that the temperature pinch point has shifted from the inlet of the evaporator to the inlet of the preheater. This value of the geothermal fluid inlet temperature ($T_{geo,in}$) is called the maximum temperature ($T_{geo,max}$). At $T_{geo,in}=T_{geo,max}$ specified working fluid also achieves the W_{NET} value which, in comparison with other working fluids, at the same geothermal fluid inlet temperatures, is among the highest (if not the highest), which is strictly true for dry and isentropic working fluids and depends on the size of Jacob's number (Ja). The value of $T_{geo,max}$ depends on the thermodynamic characteristics of the working fluid, his (subcritical) maximum pressure, the evaporator temperature pinch point and the superheating temperature difference. The greater the difference between the maximum temperature ($T_{geo,max}$) and the geothermal fluid inlet temperature ($T_{geo,in}$), the higher is the outlet temperature of the geothermal fluid (point A in Figure 2.). The higher the exit temperature of the geothermal fluid, the greater the potential for heat production (Q_{DH} and Q_{LTDH}) for the needs of district heating (DH) or low temperature district heating (LTDH), which is symbolically indicated by the shaded area in Figure 2. The size of that area (triangle 11, 19 and 12 on Figure 2.) represents the district heating potential of the SORC configuration. For double stage organic Rankine cycle (DS SORC) configuration, the specified area represents the second stage (low temperature stage) power production potential. Due to the mentioned facts, for some working fluid at the inlet temperature of the geothermal fluid ($T_{geo,in}$) that is lower than $T_{geo,max}$, the produced net power output (W_{NET}) will always be higher in the DS ORC configuration compared to the SORC configuration.

In the CHP SORC configuration, after the geothermal fluid exits the evaporator, it is possible to use a split flow strategy and divide the geothermal fluid flow into two parts, one of which is used for preheat the working fluid in the preheater, while the other flow of geothermal fluid can be used for production of heat flow for district heating (DH) or low temperature district heating (LTDH). The geothermal fluid flow used to preheat the working fluid in the preheater should be minimal, which has the consequence that pinch point temperature difference (between the geothermal fluid and the working fluid) is formed at the entrance to the preheater (9 °C in our case).

In the CHP DS ORC configuration, after the geothermal fluid exits the evaporator in low temperature stage (LTS), it is possible to use a split flow strategy and divide the geothermal fluid flow into two parts, one of which is used for preheat the working fluid in the LTS preheater, while the other flow of geothermal fluid can be used for production of heat flow for district heating (DH) or low temperature district heating (LTDH). The geothermal fluid flow used to preheat the working fluid in the LTS preheater should be minimal, which has the consequence that pinch point temperature difference (between the geothermal fluid and the working fluid) is formed at the entrance to the preheater (9 °C in our case).

Thermodynamic System Models and Assumptions

Each component in the ORC configuration is defined as a control volume, for which thermodynamic expressions are defined in accordance with the mass conservation principle and first law of the thermodynamics. For CHP ORC configurations subcooling in the condenser and superheating of working fluid are provided, which describe more realistic plant operation. During optimization routine design variables, or independent variables, are determined. In order to make this possible, assumed constant values of fixed variables, or model parameters, must be included in the thermodynamic model. Model parameters, assumptions and their selected values are in accordance with the values that are common in the scientific literature *(Mustapić et al., 2024)*. For both considered CHP ORC configurations, optimization was performed in such a way that the maximum value of net power output (W_{NET}) was determined, and at the same time how much heat can be produced for district heating purposes. Considered geothermal sources temperatures are 120°C, 140° C, 160° C and 180°C.

Selected Working Fluids

Selection the appropriate working fluid represents one of the most important actions during the design of an CHP ORC plant. Properties of the working fluids that must be considered when choosing the best solution, it is possible to divide into a number of categories. The list of categories and their corresponding properties of the working fluid are shown in Table 1. Nowadays, in addition to good thermodynamic characteristics, working fluids must also have good environmental characteristics. Ozone depletion potential (ODP) and global warming potential (GWP) are most often used as environmental factors. Therefore, it is desirable that the selected working fluid has zero ODP and a low GWP value (lower than 150), but also very good thermodynamic characteristics. Between selected working fluids, two working fluids are Hydrofluoroolefins (R1234yf and R1234ze(E)), five working fluids belong to Hydrochlorofluorocarbon refrigerants (R245fa, R236fa, R227ea, R134a and 143a), RC318 is Perfluorocarbon, while the rest are Hydrocarbons (cyclopentane, isopentane (R601a), n-pentane (R601), n-butane (R600), isobutane (R600a), propane (R290) and propylene (R1270)). Selected working fluids and their main characteristics are shown in Table 2.

Table 1. Properties of working fluids that must be considered when choosing the best solution
Tablica 1. Svojstva radnih fluida koja se moraju uzeti u obzir pri izboru najboljeg rješenja

Thermodynamic		Process related		Technical	
1.	Density	8.	Efficiency	11.	Availability and cost
2.	Latent heat of vaporization	9.	Maximum operation pressure	12.	Vapour curve (isentropic, wet and dry working fluids)
3.	Liquid heat capacity	10	Critical pressure	13.	Thermal stability
4.	Viscosity			14.	Compatible with lubricating oil
5.	Thermal conductivity			15.	Material capability
6.	Melting point temperature			16.	Condensing pressure
7.	Critical temperature				
Safety		**Environmental**			
17.	Toxicity	19.	Ozone depletion potential (ODP)		
18.	Flammability	20.	Global warming potential (GWP)		

RESULTS AND DISCUSSION

The combined production of heat and power (CHP) can be characterized by CHP ORC plant (system) efficiency and can be expressed using the expression:

$$\eta_{CHP,\frac{DH}{LTDH}} = \frac{W_{NET} + Q_{\frac{DH}{LTDH}}}{Q_{AV}} \qquad [1]$$

where W_{NET} is the produced net power, $Q_{DH/LTDH}$ represents the produced heat for district heating (DH) or low temperature district heating (LTDH), while Q_{AV} represents the available heat that can be processed in the plant. Another thermodynamic parameter that characterizes CHP ORC production is CHP coefficient is defined as the ratio between net power and produced heat for district heating (DH) or low temperature district heating (LTDH) and can be expressed by the equation:

$$\sigma_{DH/LTDH} = \frac{W_{NET}}{Q_{DH/LTDH}} \qquad [2]$$

The assumed district heating (DH) supply temperature is 80 °C, while the return temperature is 60 °C. The geofluid transfers the heat flow to the DH system until it cools down to 70 °C, to avoid excessive temperature cross in the heat exchanger. For the LTDH system, a supply temperature of 60 °C is assumed, while the return temperature is 40 °C. The geofluid outlet temperature from the LTDH heat exchanger is 50 °C.

Table 2. Selected working fluids and their characteristics (P_{cr} – critical point pressure, T_{cr} – critical point temperature, ODP - ozone depletion potential, GWP - global warming potential, $T_{geo,max}$ – maximum geothermal temperature, $\Delta T_{crit,max}=T_{geo,max}-T_{cr}$)

Tablica 2. Odabrani radni fluidi i njihove karakteristike (P_{cr} – kritični tlak, T_{cr} – kritična temperatura, ODP - potencijal deplatacije ozona, GWP - potencijal globalnog zatopljenja, $T_{geo,max}$ – maksimalna geotermalna temperatura, $\Delta T_{crit,max} = T_{geo,max} - T_{cr}$)

Name	P_{cr} (bar)	T_{cr} (°C)	Safety group	ODP	GWP	Type	$T_{geo,max}$ (°C)	$\Delta T_{crit,max}$ (°C)
Cyclopentane	45,71	238,6	A3	0	11	dry	374,4	135,8
n-Pentane (R601)	33,64	196,5	A3	0	20	dry	316,6	120,1
Isopentane (R601a)	33,70	187,2	A3	0	20	dry	299,5	112,3
R245fa	36,51	154,0	B1	0	1050	isentropic	201,3	47,3
n-Butane (R600)	37,96	152,0	A3	0	3	dry	200,1	48,1
R236ea	34,29	139,3	-	0	1410	isentropic	183,4	44,1
isobutane (R600a)	36,40	134,7	A3	-	0	dry	181,3	46,6
R236fa	32,00	124,9	A1	0	9810	dry	168,8	43,9
RC318	27,78	115,2	A1	-	10300	dry	153,2	38,0
R1234ze(E)	36,32	109,4	A2L	-	6	isentropic	156,5	47,1
R227ea	29,25	101,8	A1	0	3220	dry	142,2	40,4
R134a	40,59	101,0	A1	0	1430	isentropic	156,2	55,2
Propane (R290)	42,47	96,68	A3	-	0	wet	150,6	53,9
R1234yf	33,82	94,70	A2L	0	4,4	dry	139,3	44,6
Propylene (R1270)	46,65	92,42	A3	-	1,8	wet	151,8	59,4
R143a	37,61	72,70	A2	0	4470	wet	121,8	49,1

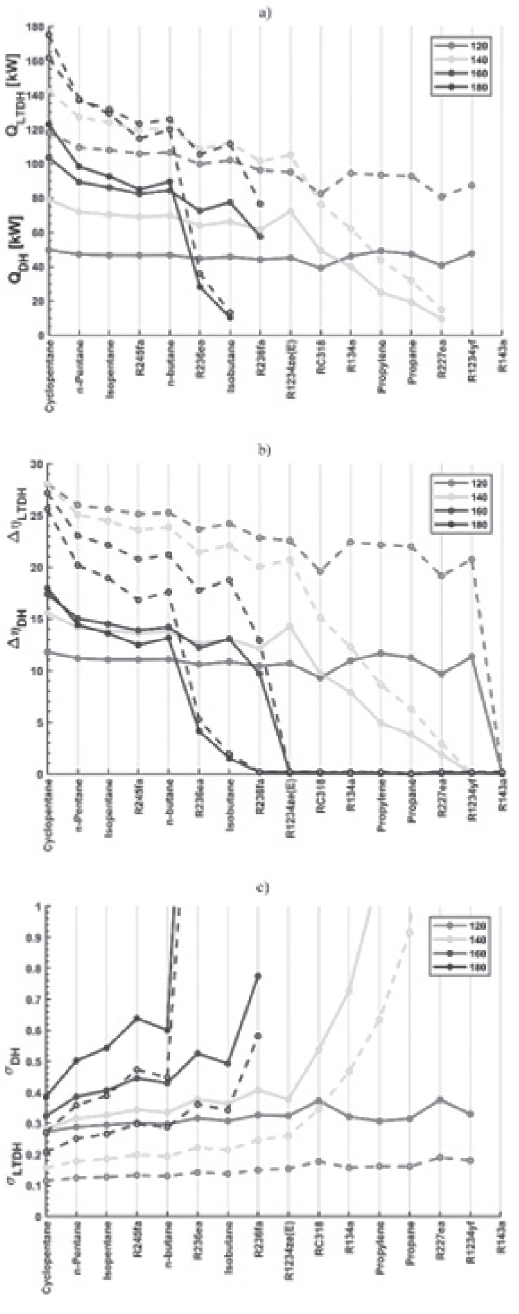


Figure 3. Results for the CHP SF SORC configuration for different working fluids and characteristic inlet temperatures of the geothermal fluid: a) Q_{DH} and Q_{LTDH}, b) $\Delta\eta_{DH}$ and $\Delta\eta_{LTDH}$, c) σ_{DH} and σ_{LTDH}

Slika 3. Prikaz rezultata za kogeneracijsku konfiguraciju jednostavnog Rankineovog ciklusa s organskim fluidom s razdvajanjem toka geotermalnog fluida (CHP SF SORC) za različite radne fluide i karakteristične ulazne temperature geotermalnog fluida: a) Q_{DH} i Q_{LTDH}, b) $\Delta\eta_{DH}$ i $\Delta\eta_{LTDH}$, c) σ_{DH} i σ_{LTDH}

Figure 3. shows the essential results for the CHP SF SORC configuration for different working fluids and characteristic temperatures of the geothermal fluid. It should be noted that on the pictures, the working fluids are ordered by size of the $T_{geo,max}$. Figure 3.a) shows the produced heat flows for the needs of district heating (Q_{DH}) and low temperature district heating (Q_{LTDH}). In general, it can be concluded that the produced heat flows are significantly higher for the low temperature district heating (Q_{LTDH}) then for the district heating (Q_{DH}). The main reason for this is lower supply and return temperatures for the low temperature district heating (LTDH). It can be noticed that value of the Q_{DH} and Q_{LTDH}, with the same value of geothermal fluid, decreases with working fluids that have a lower value of $T_{geo,max}$. For the same working fluid, Q_{DH} and Q_{LTDH} increase with increasing temperature of the geothermal fluid inlet temperature, which is especially visible for the DH. However, in LTDH for the same working fluid, Q_{LTDH} values for different geothermal fluid temperatures are quite similar. As the temperature of the geothermal fluid increases, the mass flow of the geothermal fluid in the LTDH heat exchanger decreases, while the unit heat flow output to LTDH increases. The negative increment of the geothermal fluid flow for LTDH needs is greater, so it is possible that with geothermal fluid temperature rise, the values of Q_{LTDH} stagnate, slightly decrease or increase. A good example is R236ea, which for geothermal fluid temperatures from 120 °C to 160 °C has very similar Q_{LTDH} values. For a geothermal fluid temperature of 120 °C, almost all considered working fluids can achieve QDH and QLTDH, except for the working fluid R143a ($T_{gei,in}$ is greater than $T_{geo,max}$). The Q_{DH} values are very similar and range from 39.19 kW/(kg/s) for RC 318, to 49.68 kW/(kg/s) for cyclopentanes. At the same time, RC 318 achieves 14.63 kW/(kg/s) net power output (W_{NET}), and cyclopentane achieves 13.52 kW/(kg/s). The highest amount of net power output (W_{NET}) is achieved by R1234yf with simultaneous district heating heat production of 47.67 kW/(kg/s). As the temperature of the geothermal fluid increases, the number of working fluids that can realize Q_{DH} or Q_{LTDH} is decreased due to the fact that their temperature $T_{geo,\ max}$ is lower than the inlet temperature of the geothermal fluid. The higher the working fluid temperature $T_{geo,max}$ is, the higher value of the Q_{DH} and Q_{LTDH} can be realized.

Figure 3.b) shows the values of $\Delta\eta_{DH}$ and $\Delta\eta_{LTDH}$, which represent the difference (in %) between CHP plant (system) efficiency and plant (system) efficiency without production of heat flows Q_{DH} or Q_{LTDH}. The general conclusion is that the introduction of combined heat and power (CHP) increases the energy efficiency of the plant. The effect is greater in LTDH, where plant (system) efficiency can be increased up to 28%. When DH is analysed, the results are more modest, so that the plant (system) efficiency usually increases from cca 12% to 18% depending on the working fluid and the temperature of the geothermal fluid. In general, it can be concluded that considered CHP SF ORC configuration is more suitable for combined heat and power production in the LTDH system, where a higher heat flow, more favourable CHP coefficient values and higher CHP plant (system) efficiency are realized than in the DH system.

The CHP coefficient values for district heating and low temperature district heating (σ_{DH} and σ_{LTDH}), for different geothermal fluid inlet temperatures and considered working fluids, are shown in Figure 3.c). CHP coefficient values are better for LTDH than for DH. The smaller the value of the CHP coefficient is, it means that for a certain value of W_{NET}, a larger share of heat is produced for DH or LTDH. For DH and LTDH, the lower the temperature of the geothermal fluid is, the lower is the CHP coefficient. The explanation is the same as that given for Q_{LTDH} and Q_{DH}. In the case of DH, the CHP coefficient values (σ_{DH}) are greater than one (sometimes greater than 2), which means that WNET is greater than the produced heat flow Q_{DH}.

Figure 4. shows the essential results for the CHP DS SORC configuration for different working fluids and characteristic temperatures of the geothermal fluid. It should be noted that on the pictures, the working fluids are ordered by size of the $T_{geo,max}$. Figure 4.a) shows the produced heat flows for the needs of district heating (Q_{DH}) and low temperature district heating (Q_{LTDH}) in the CHP DS ORC configuration. In general, it can be concluded that the produced heat flows are significantly higher for the low temperature district heating (Q_{LTDH}) then for the district heating (Q_{DH}). The main reason for this is lower supply and return temperatures for the low temperature district heating (LTDH). It can be noticed that value of the Q_{DH} and Q_{LTDH}, for same geothermal fluid, in general decreases with working fluids that have a lower value of $T_{geo,max}$. For the same working fluid, Q_{DH} and Q_{LTDH} increase with increasing temperature of the geothermal fluid inlet temperature, but the number of working fluids that can realize CHP production is reduced. An effect was observed in the CHP DS ORC configuration that as the temperature of the geothermal fluid inlet temperature approaches $T_{geo,max}$, the share of produced net power in HTS ($W_{NET,HTS}$) in the total produced WNET increases and the amount of heat processed in the ORC increases, and the share of the heat flow (mass flow) which separates for DH and LTDH decreases. This logically results in the reduction of Q_{DH} and Q_{LTDH} production. Similar to CHP SF SORC was observed, that in LTDH for the same working fluid, Q_{LTDH} values for different geothermal fluid temperatures are quite similar, and the explanation for that phenomenon is the same as for the CHP SF SORC configuration. In general, it can be concluded that the CHP DS ORC configuration has a significantly lower potential for heat production, then CHP SF SORC configuration, for the needs of district heating and low temperature district heating. Even for a geothermal fluid input temperature of 120 oC, a district heating supply temperature of 80 °C cannot be achieved. For this reason, it can be concluded that the CHP DS ORC configuration is not suitable for the cogeneration production, especially at low values of geothermal fluid temperatures.

Figure 4.b) shows the values of $\Delta\eta_{DH}$ and $\Delta\eta_{LTDH}$ for CHP DS ORC configuration. The effect is greater in LTDH, where plant (system) efficiency can be increased up to 18%. When DH is analyzed, the results are more modest, so that the plant (system) efficiency usually increases from 5% to 8% depending on the working fluid and the temperature of the geothermal fluid.

The CHP coefficient values for district heating and low temperature district heating (σ_{DH} and σ_{LTDH}), for different geothermal fluid inlet temperatures and considered working fluids, are shown in Figure 4.c) for CHP DS ORC configuration. Also, for CHP DS ORC configuration CHP coefficient have lower values for LTDH than for DH. However, for the CHP DS ORC configuration, compared to the CHO SF ORC configuration, the values of both coefficients have significantly worse values. For example, the produced amount of heat for district heating (Q_{DH}) is always lower than the produced net power (W_{NET}), so $\sigma_{\_DH}$ always has a value greater than one.

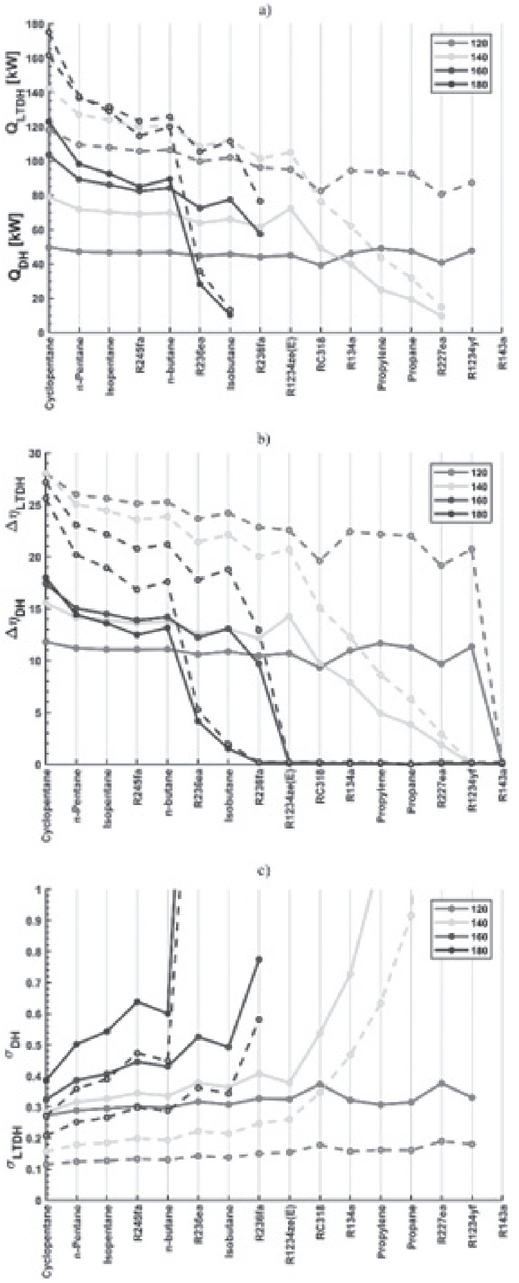


Figure 4. Results for the CHP DS ORC configuration for different working fluids and characteristic inlet temperatures of the geothermal fluid: a) Q_{DH} and Q_{LTDH}, b) $\Delta\eta_{DH}$ and $\Delta\eta_{LTDH}$, c) σ_{DH} and σ_{LTDH}

Slika 4. Prikaz rezultata za kogeneracijsku konfiguraciju dvostupanjskog Rankineovog ciklusa s organskim fluidom za različite radne fluide i karakteristične ulazne temperature geotermalnog fluida: a) Q_{DH} i Q_{LTDH}, b) $\Delta\eta_{DH}$ i $\Delta\eta_{LTDH}$, c) σ_{DH} i σ_{LTDH}

CONCLUSION

From a thermodynamic, economic, but also ecological point of view, geothermal organic Rankine cycle (ORC) plants should primarily be designed in such a way that simultaneously with the production of electricity produce thermal energy that is distributed in district heating or in the future in low temperature district heating systems. That is reason why optimal combined heat and power organic Rankine cycle (CHP ORC) design is attracting increased interest from experts and scientists.

After performed thermodynamic analysis, it can be concluded that the proposed CHP ORC configurations is more suitable for combined heat and power production in the LTDH system, where a higher heat flow, more favorable CHP coefficient values and higher CHP plant (system) efficiency are realized than in the DH system. In general, it can be concluded that the CHP DS ORC configuration has a significantly lower potential for heat production, then CHP SF SORC configuration, for the needs of district heating and low temperature district heating.

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KOMBINIRANA PROIZVODNJA TOPLINE I ELEKTRIČNE ENERGIJE IZ GEOTERMALNIH IZVORA KORIŠTENJEM RAZDVAJANJA TOKA I NAPREDNE DVOSTUPANJSKE KONFIGURACIJE RANKINOVOG CIKLUSA S ORGANSKIM FLUIDOM

SAŽETAK: Zbog sve većih potreba za električnom energijom i decentralizacijom proizvodnje električne energije, posebice zbog potrebe za proizvodnjom električne energije iz obnovljivih izvora, izgradnja elektrana temeljenih na Rankinovom ciklusu s organskim fluidom postaje prioritetni cilj. Međutim, kod ovakvog tipa elektrana, kombinirana proizvodnja toplinske i električne energije (kogeneracija) omogućuje dodatno smanjenje gubitaka toplinske energije i povećanje ukupne učinkovitosti elektrane zasnovane na Rankinovom ciklusu s organskim fluidom. Cilj ovog rada jest odrediti i usporediti termodinamička svojstva dvaju konfiguracija Rankinovog ciklusa s organskim fluidom za kombiniranu proizvodnju toplinske i električne energije (kogeneracija) osnovnog ciklusa s razdvajanjem toka geotermalnog fluida i dvostupanjskog ciklusa. Temperature razmatranih srednjetemperaturnih i niskotemperaturnih geotermalnih izvora kreću se od 120°C do 180°C. Primijenjena metodologija istraživanja sastoji se od termodinamičke analize i optimizacije navedenih konfiguracija za proizvodnju toplinske i električne energije iz geotermalnih izvora. Dobiveni rezultati sugeriraju da osnovna konfiguracija s razdvajanjem tokova geotermalnog fluida ostvaruje bolje rezultate od dvostupanjske konfiguracije te se učinkovitost postrojenja može povećati za 28 % pri niskim temperaturama geotermalnog fluida, a kogeneracijska učinkovitost povećava se od 12 % do 18 % ovisno o vrsti radnog fluida i temperaturi geotermalnog fluida. Kod kogeneracijskog dvostupanjskog Rankinovog ciklusa s organskim fluidom, učinkovitost postrojenja može se povećati do 18 % niskim temperaturama geotermalnog fluida, a kogeneracijska učinkovitost postrojenja povećava se od 5 % do 8 %.

Ključne riječi: *Rankinov ciklus s organskim fluidom, geotermalna energija, kombinirana proizvodnja toplinske i električne energije, princip razdvajanja toka, dvostupanjska konfiguracija*

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