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INFLUENCE OF WORKING FLUID ON ORC WITH LOW TEMPERATURE GEOTHERMAL SOURCE – CASE STUDY GEOTHERMAL POWER PLANT "BABINA GREDA"

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ABSTRACT

In 1998 the Energy Institute "Hrvoje Požar" prepared a Program of Geothermal Energy Usage in the Republic of Croatia, which shows that in the Republic of Croatia there are some low/medium temperature geothermal sources (geothermal water) in the range from 100 to 170 ºC, by means of which it is possible to produce electricity in binary plants, either with the Organic Rankine Cycle (ORC) or with the Kalina cycle. However concrete initiatives for the construction of geothermal power plants have only recently been started. In accordance with this authors in previous papers have presented result of an energy-exergy analysis of geothermal resources Velika Ciglena (175 ºC), Lunjkovec-Kutnjak (140 ºC), Babina Greda (125 ºC) and Rečica (120 ºC), in order to determine which cycle is better for the conditions in Croatia. The analysis results have shown that the ORC with isopentane as working fluid is thermodynamically better from the Kalina cycle for temperatures of all cited geothermal sources and cooling air, and considering the problems that all the new technologies as Kalina cycle encounter in their early phase of application, authors propose the application of binary plants using ORC cycle for all low/medium temperature geothermal sources in the Republic of Croatia. Researches related to the application of the ORC generally deals with the selection of the working fluid, optimization of the ORC unit and the whole plant and analysis of possible modifications with aim to increase its thermodynamic efficiency or net mechanical power output. Although in the available literature, there are a large number of published research results on the selection of the working fluid, however, every geothermal source is a case for itself with respect to the temperature of geothermal water and the cooling fluid on location (water or air). Therefore, in this paper will be presented the results of analysis of the working fluid influence on both thermodynamic efficiency and useful work and others plant characteristics for the case of Geothermal Power Plant "Babina Greda" with lower temperature of geothermal water - 125 ºC. As the working fluid the next refrigerants and hydrocarbons will be analyzed: R236fa, toluene, R365mfc, R236ea, C5F12, hexane, R123, R245ca, R245fa, R21, R114, R113, R12, R11, R152a, R142b, R141b, R600a, R600, R601a and R601.

INTRODUCTION

Geothermal energy is the energy contained in the Earth's interior. Generally, geothermal energy is a clean energy source, as it meets the criteria of two important concepts in energy source exploitation: renewability and sustainability. The increase in temperature with depth is referred to as a geothermal temperature gradient. A local geothermal gradient is essential for geothermal energy exploitation because it indicates the presence of geothermal resources at reachable depths [1]. Presently, an international standard on terminology for the classification of geothermal sources is not yet defined. The most widely used classification of geothermal sources is based on the temperature of the geothermal fluid. Geothermal sources are divided into low- (<100 ºC), medium- (100 – 200 ºC) and high-temperature sources (> 200 ºC) [2].

Currently, geothermal energy is used either indirectly (for electricity generation) or directly (in district heating, greenhouses, swimming pools, for medical purposes (spa), in fish farming and in various industrial processes), thus producing savings in the use of conventional energy sources. The total installed capacity of geothermal power plants in the world at the end of 2010 was approximately 10,700 MW, Figure 1, now 11.766 GW, while forecasting of the installed capacity in 2015 is 18.5 GW [3]. At the same time the total installed capacity worldwide at the end of 2009 for direct geothermal utilisation was 50,583 MW [4]. Countries that are increasingly using geothermal energy sources for electricity production or for direct application include the United States, Iceland (where geothermal power accounts for 44% of the total energy consumption), Italy, New Zealand, France, Germany and Hungary [3, 4].

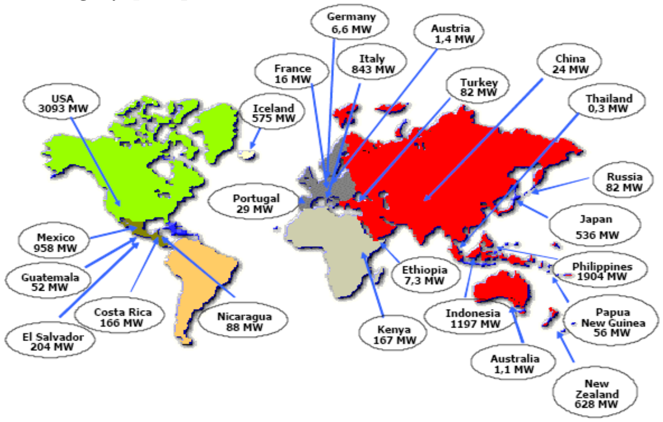

Figure 1 Installed capacity in 2010 worldwide - 10.7 GW [3]

In the Republic of Croatia, there is a several-centuries-old tradition of exploiting geothermal energy for medical purposes and for bathing. In addition to the use of geothermal energy in spas, techniques and technologies for obtaining geothermal energy from deep geothermal reservoirs were developed as a result of research into oil and gas resources. With the development of the oil industry in the Republic of Croatia and the comparative testing of certain geothermal wells, a technological basis was created for exploiting geothermal water for recreational-medical purposes, heating, production of fruits and vegetables in greenhouses, and for the subsequent industrial thermal processing of such products (e.g., drying and pasteurisation).

As early as 1998, the Energy Institute, Hrvoje Požar, prepared a Program of Geothermal Energy Usage in the Republic of Croatia [5]. This report showed that in the Republic of Croatia, there are several medium-temperature geothermal sources with a relatively lower temperature of geothermal water in the range of 90–175 ºC, from which it is possible to produce electricity. However, concrete initiatives for the construction of geothermal power plants have only recently been taken.

For the generation of electricity from these geothermal sources, the binary plants come to the fore, either with the ORC or with the Kalina cycle. The comparison of these two cycles is performed on the basis of the results of energy-exergy analysis of previously mentioned geothermal fields in the Republic of Croatia [6-10]. In all cases, the ORC was thermodynamically better than the Kalina cycle, and it is proposed as a solution for the production of electricity from geothermal energy in the Republic of Croatia.

The working fluid plays a key role in the ORC: affects system efficiency, operating conditions, environmental impact and economic viability. Therefore, this paper analyses the influence of the 21 screened working fluid on ORC performance at conversion of low-grade geothermal energy into electricity in case Geothermal Power Plant "Babina Greda".

NOMENCLATURE

$\bar{c}$	[J/kgK]	Average specific heat
h	[J/kg]	Specific enthalpy
$\dot{m}$	[kg/s]	Mass flow rate
p	[Pa]	Pressure
$\dot{Q}$	[W]	Heat flow rate
s	[J/kgK]	Specific entropy
T	[K], [ºC]	Temperature
$\dot{V}$	[m^3/s]	Volumetric flow rate
$\dot{W}$	[W]	Work flow rate-power

Special characters

Δ	[-]	Difference, e.g. of pressure
η	[-]	Efficiency

Subscripts

bp	Boiling point
crit	Critical
cf	Cooling fluid
f	Fan
gf	Geothermal Fluid
in	Input
is	Isentropic state
net	Net
max	Maximum
min	Minimum
out	Output
p	Pump
plant	Plant
t	Turbine
0	Ambient
1-17	Points on plant scheme or *T*-*s* diagram

GEOTHERMAL POTENTIAL IN CROATIA FOR ELECTRICITY PRODUCTION

The Republic of Croatia has many centuries of tradition of geothermal energy usage from natural springs for medical purposes and bathing. Geothermal energy is the basis of the economic success of numerous spas in Croatia.

There is a total of 28 geothermal fields, out of which 18 are in usage. For the needs of space heating a total of 36.7 MW of heating power has been installed with annual usage of heating energy of 189.6 TJ/year. For bathing 77.3 MW of heating power is used, i.e. 492.1 TJ/year. Until now, geothermal energy was not used for the production of electricity [5].

Along with the research activities regarding oil and gas, Croatia has also developed the technique and technology for obtaining geothermal energy from deep geothermal layers. At the same time, abandoned oil wells could be considered for geothermal energy utilization [11].

The two sedimentary basins cover almost the entire territory of the Republic of Croatia: the "Pannonian" basin and the "Dinarides" basin, Figure 2 [5]. Large differences between these two basins are in geothermal potentials which have been obtained by investigation works with the aim of discovering oil and gas.

In the "Dinarides" basin the average geothermal temperature gradient and heat flux are 0.018 ºC/m and 29 mW/m^2 [5].

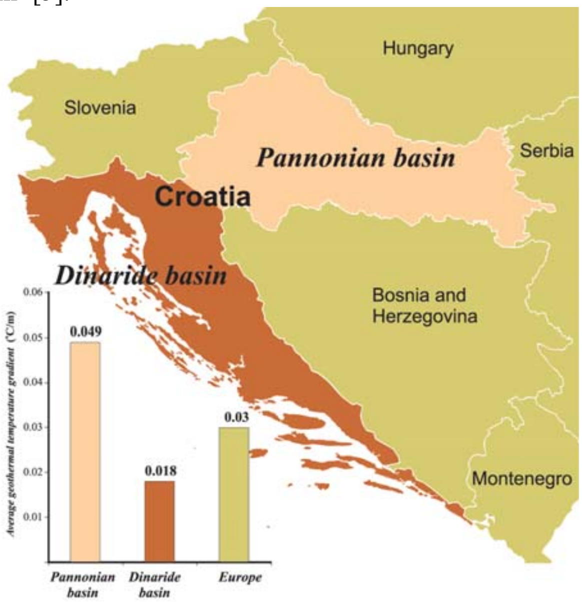

Figure 2 Geothermal temperature gradient in The Republic of Croatia [5]

Unlike the "Dinarides" basin, which has no significant geothermal potentials, the average geothermal temperature gradient and heat flux in the "Pannonian" basin are much greater: 0.049 ºC/m and 76 mW/m^2 [5]. Since the geothermal gradient in the "Pannonian" basin is considerably greater than the European average value, in this region, besides the already discovered geothermal fields, the discovery of new geothermal fields is to be expected.

Geothermal potentials in Croatia can be divided into three groups, Figure 3: the medium temperature sources with 100–200 ºC; low temperature sources with 65–100 ºC and geothermal sources with water temperature below 65 ºC [5].

The entire heating power of geothermal energy potential of Croatia from the already worked-out wells is estimated at 203.47 MW (up to 50 ºC) i.e. 319.21 MW (up to 25 ºC), and with complete work out fields 839.14 MW (up to 50 ºC) i.e. 1169.97 MW (up to 25 ºC) [5].

In the Republic of Croatia there are several medium temperature geothermal sources with temperature in the range of 100–200 ºC (Figure 3), by means of which it is possible to produce electricity: Velika Ciglena (175 ºC), Lunjkovec (145 ºC), Ferdinandovac (125 ºC), Babina Greda (125 ºC) and Rečica (120 ºC). From the review of today's available technologies for the generation of electricity from these geothermal sources, the binary plants come to the fore, either with the ORC or with the Kalina cycle. In previous works [6-10] for all cited medium temperature geothermal resources in the Republic of Croatia, the comparison of these two cycles is performed on the basis of energy and exergy analysis.

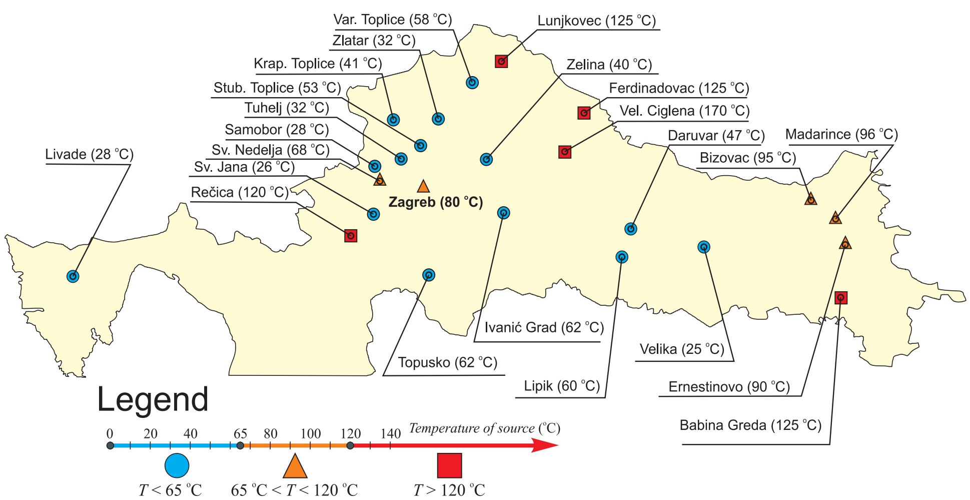

Figure 3 Geothermal potentials in The Republic of Croatia [5]

Binary plants convert medium temperature resources into electricity more efficiently than other technologies. In binary plants a heat exchanger transfers heat from the produced hot geofluid in a primary loop to a low boiling-point working fluid in a secondary loop, such as propane, isobutene, pentane, isopentane, etc. This thermodynamic cycle is known as Organic Rankine Cycle (ORC) because initially organic compounds were used as the working fluid (Figure 4). The working fluid in the secondary loop is evaporated in the vaporizer by the geothermal heat provided in the primary loop. The vapour expands as it passes through the organic vapour turbine which is coupled to the generator. The exhaust vapour is condensed in a water-cooled condenser or air cooler and is recycled to the vaporizer by the feed pump. The cooled geofluid can be discharged or reinjected into the reservoir without flashing, which minimizes scaling problems.

ORC systems have been installed in significant numbers within the past 30 years because binary plants convert medium enthalpy geothermal resources more efficiently into electricity than other technologies, which widens the spectrum of locations suitable for geothermal power production significantly. It makes decentralized geothermal production feasible and economically attractive in many remote or less developed regions of the world, where financial incentives promote low CO_2 emission energy production technologies.

Recently, the efficiency of binary power plants has been further improved by the Kalina Cycle technology (Figure 5). Here, a mixture of water and ammonia (NH_3) is evaporated over a finite temperature range, producing a two-component vapour in contrast to the ORC which is based on pure fluids evaporating at specific boiling temperatures. The main thermodynamic advantage of the Kalina cycle over the ORC is due to the fact that the water-ammonia mixture, unlike pure fluids, boils at variable temperatures. Therefore the working fluid temperature remains closer to the temperature of the hot geofluid in the primary circuit which improves the exergy efficiency.

The proposed binary plants, basic ORC (Figure 4) and Kalina cycle (Figure 5) with regard to configurations and cycle working parameters (maximal pressure and temperature, mixture composition, etc.) are chosen in such a way that they are very close to the performed, type-designed plants of the leading world manufacturers. Since at the locations of the geothermal fields in Croatia the amounts of cooling water for the water-cooled condenser are not sufficient, in both cases, the air-cooled condensers are used, whose thermodynamic calculations have been performed with the average annual air temperature of 15 ºC. The working fluid in the ORC is a low boiling-point isopentane, and in the Kalina cycle, a mixture of water and ammonia, whose composition changes during the cycle. The presumed turbine isentropic efficiencies are 0.85 for the ORC (dry turbine) and 0.75 for the Kalina cycle (wet turbine). In both cases the presumed efficiencies for feed pumps are 0.8, the same as for high pressure pump for geothermal water. In thermodynamic calculations special attention is paid to the values of pinch points which are not below 5 ºC.

Thermodynamic calculations are performed on a computer by means of binary cycle model with ORC and Kalina cycle which is developed on the basis of [1, 2, 12-19], where thermodynamic properties of working fluids are determined by REFPROP program [20]. The exergy analysis of ORC and Kalina cycle is performed by the use of REFPROP program special routine on models of the most important cycle units and both cycles developed on the basis of [1, 21-27]. The exergy balance considered T_0=298.15 K and p_0=101325 Pa as the dead state conditions for the calculation of physical exergy, and neglected the kinetic, potential and chemical exergy of the streams.

In case of all analyzed medium temperature geothermal resources, the ORC is thermodynamically better than the Kalina cycle, as it is presented in Table 1. It can be explained by relatively high temperature of cooling air in the condenser (15 ºC) which has a more unfavourable influence on the Kalina cycle than on the ORC. In such conditions, the condensation pressure in the Kalina cycle is considerably higher than in the ORC. Thus for all medium temperature geothermal sources in Croatia (Velika Ciglena, Lunjkovec, Ferdinandovac, Babina Greda and Rečica) the application of the binary plants with ORC are proposed.

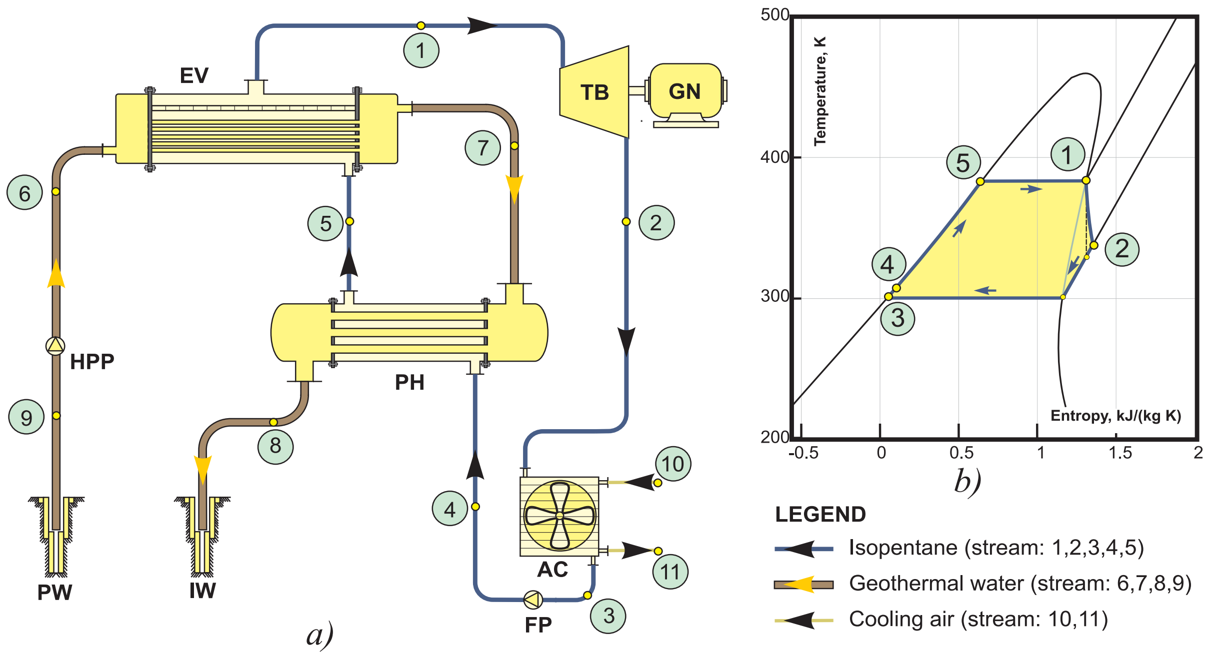

Figure 4 Binary cycle with the ORC: *a*) scheme of a plant (HPP-high pressure pump, FP-feed pump, PH-preheater, EV-evaporator, AC-air condenser, TB-turbine, GN-generator, PW production well, IW-injection well) and *b*) temperature– entropy diagram [6]

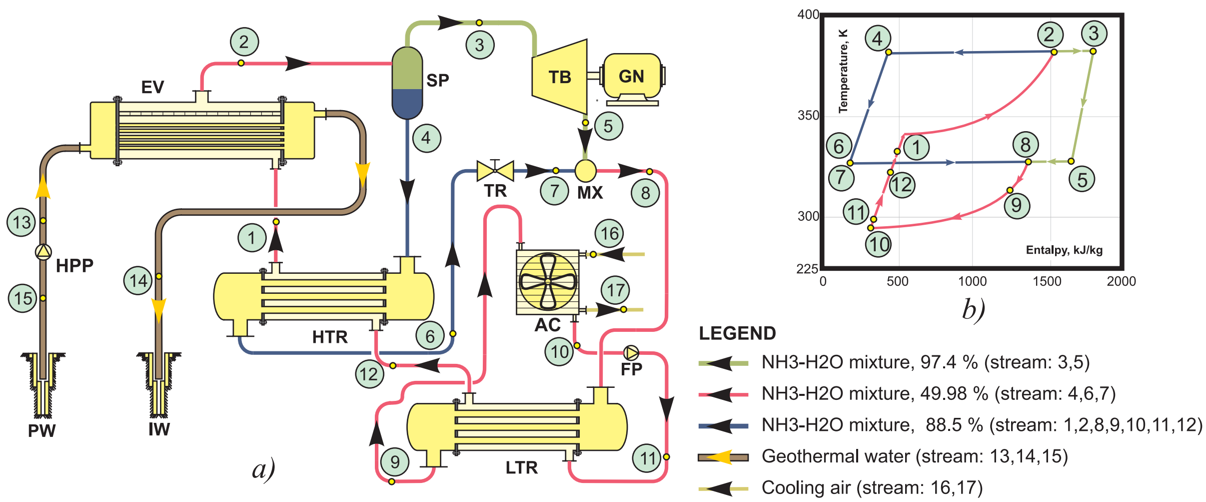

Figure 5 Binary cycle with the Kalina cycle: *a)* scheme of a plant (HPP-high pressure pump, FP- feed pump, LTR- low temperature preheater, HTR-high temperature preheater, EV-evaporator, SP-separator, MX-mixer, TR-throttle valve, AC-air condenser, TB-turbine, GN- generator, PW-production well, IW-injection well) and *b)* temperature–enthalpy diagram of the binary cycle with the Kalina cycle [6]

Table 1 The comparison of ORC and Kalina cycle on the basis of the results of energy-exergy analysis in cases of geothermal fields in the Republic of Croatia by means of which it is possible to produce electricity [6-10]

Geothermal field	Geothermal fluid			Organic Rankine Cycle (ORC)			Kalina cycle		
	Flow rate [kg/s]	Input temperature [°C]	Output temperature [°C]	Cycle net power [kW]	1st Law efficiency [%]	2nd Law efficiency [%]	Cycle net power [kW]	1st Law efficiency [%]	2nd Law efficiency [%]
Velika Ciglena	83.0	175	69	5270	14.1	52	3949	10.6	44
Lunjkovec-Kutnjak	64.87	140	80	2225.5	13.5	46.2	2101.4	12.8	43
Babina Greda	93.97	125	70	2509.9	11.5	46.3	2317.4	10.7	42.7
Rečica	94.38	120	80	1964.1	12.4	35.9	1872.4	11.8	34.2

MATHEMATICAL MODEL OF ORC

Thermodynamic modelling is necessary for the calculation of all parameters in a power plant and for making models for each power plant before design of a power plant can be started. Thermodynamics of the conversion processes in single components of the binary plants with ORC is given in [1, 2, 12-19]. The following mathematical model of ORC is used to analyze thermodynamic behaviour of ORC plant. Pressure drops occured in various components and pipes are not considered. Figure 4 a,b shows the conditions of working fluid at different locations and paths of energy conversion in an ORC, and denotations in the next equations correspond to those in Figure 4 a,b. The obtained equations which make the mathematical model are summarized below.

The power of the turbine in the ORC is given by:

$$\dot{W}_t = \dot{m}_{wf}\left(h_1 - h_2\right) = \dot{m}_{wf}\eta_t\left(h_1 - h_{2is}\right) \tag{1}$$

The relationship between the flow rates of the working fluid and the geothermal fluid in the heat exchanger (in pre-heater PH and evaporator EV) in the ORC is:

$$\dot{m}_{gf}\left(h_6 - h_8\right) = \dot{m}_{wf}\left(h_1 - h_4\right), \tag{2.a}$$

or

$$\dot{m}_{gf}\bar{c}_{gf}\left(T_6 - T_8\right) = \dot{m}_{wf}\left(h_1 - h_4\right) \tag{2.b}$$

The following equation may be used to determine the working fluid flow rate in ORC:

$$\dot{m}_{wf} = \frac{\dot{m}_{gf}\bar{c}_{gf}\left(T_6 - T_8\right)}{h_1 - h_4} \tag{3}$$

The pre-heater PH and evaporator EV may be analyzed separately:

$$\dot{m}_{gf}\bar{c}_{gf}\left(T_7 - T_8\right) = \dot{m}_{wf}\left(h_5 - h_4\right) \tag{4.a}$$

$$\dot{m}_{gf}\bar{c}_{gf}\left(T_6 - T_7\right) = \dot{m}_{wf}\left(h_1 - h_5\right) \tag{4.b}$$

The pinch–point temperature difference is generally known from the manufacturer's specifications and T_7 can be found from the value for T_5.

The supplied heat in cycle:

$$\dot{Q}_1 = \dot{m}_{gf}(h_6 - h_5) = \dot{m}_{gf}(h_{13} - h_{14}) \quad (5.a)$$

or

$$\dot{Q}_1 = \dot{m}_{gf}\bar{c}_{gf}(T_6 - T_5) = \dot{m}_{gf}\bar{c}_{gf}(T_{13} - T_{14}) \quad (5.b)$$

The heat that must be rejected from the working fluid to the cooling fluid (air) in the condenser AC in the ORC is found from:

$$\dot{Q}_2 = \dot{m}_{wf}(h_2 - h_3) \quad (6)$$

The relationship between the flow rates of the working fluid and the cooling fluid is:

$$\dot{m}_{cf}(h_{11} - h_{10}) = \dot{m}_{wf}(h_2 - h_3), \quad (7.a)$$

or

$$\dot{m}_{cf}\bar{c}_{cf}(T_{11} - T_{10}) = \dot{m}_{wf}(h_2 - h_3) \quad (7.b)$$

since the cooling fluid has a constant specific heat $\bar{c}$ for a small temperature range.

So, the flow rate of cooling fluid (air) is:

$$\dot{m}_{cf} = \frac{\dot{m}_{wf}(h_2 - h_3)}{\bar{c}_{cf}(T_{11} - T_{10})} \quad (8)$$

The power imparted to the working fluid from the feedpump is:

$$\dot{W}_p = \dot{m}_{wf}(h_4 - h_3) = \dot{m}_{wf}(h_{4is} - h_3)/\eta_p, \quad (9)$$

The power imparted to the cooling fluid from the fan is:

$$\dot{W}_f = \dot{V}\Delta p/\eta_f \quad (10)$$

Plant net power:

$$\dot{W}_{net} = \dot{W}_t - \dot{W}_p - \dot{W}_f \quad (11)$$

The plant efficiency:

$$\eta_{plant} = \frac{\dot{W}_{net}}{\dot{Q}_1} \quad (12)$$

WORKING FLUIDS FOR ORC

Organic Rankine cycles employ pure refrigerants or hydrocarbons as working fluids [28-41]. Fluid mixtures have also proposed for ORC [42]. The organic working fluids have many different characteristics from water and can be classified as a dry, isentropic or wet fluid depending on the slope of the saturation vapour curve in *T-s* diagram, Figure 6 [35].

Wet fluids usually need to be superheated, while many organic fluids, which may be dry or isentropic, do not superheating. Very important advantage of organic working fluids is that the ORC turbine requires small number of stages, often a one stage, resulting in a simpler and more economical system. The techno-economic characteristics of a ORC strictly depend on the thermodynamic properties of the working fluid. The bad selection can lead to a low efficient and expensive plant. Therefore, many researchers analyzed the characteristics of different working fluids which they should fulfill for their suitability in ORCs.

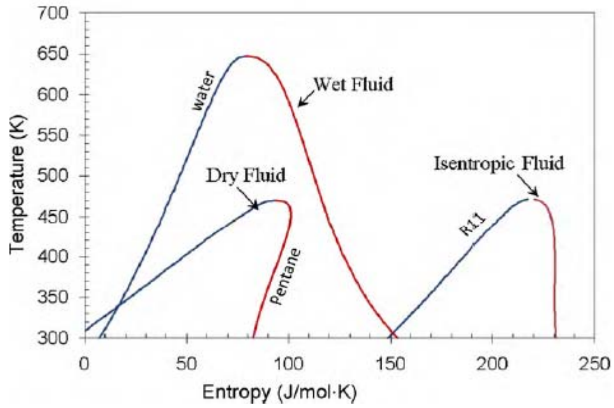

Figure 6 Three types of working fluids: dry, isentropic, and wet [35]

According to [28-41] an ideal working fluid has the next properties:

- dew point pressure at the point of initial condensation should be as low as possible (to minimize condenser cost per unit of heat transfer surface area) but greater than atmospheric pressure (to avoid leakage of air into the system;
- saturated vapour locus on a *T-s* diagram should be nearly vertical, to avoid excessive superheat in heat exchangers (small heat transfer coefficient) and condensation in the turbine (loss due to condensation and blade erosion by liquid impingement);
- large specific enthalpy change in the turbine (to maximize cycle thermodynamic efficiency and minimize workong fluid flow rate; on the other hand if specific enthalpy change becomes too large, less efficient and more costly multi-stage turbines would be required – optimum range exists);
- the turbine inlet pressure should be reasonably low (to minimize heat exchanger cost per unit of heat transfer surface area);
- a small heat of evaporization and a matching heat resource (reason is to maximize the energy utilization at the highest availability);
- a low specific heat to avoid a high load for condenser;
- specific volume at the turbine exit should be small, to keep turbine size small;
- thermal conductivity coefficients should be large (to minimize heat transfer surface area due to higher convective heat transfer coefficients);
- viscosities should be low (to minimize frictional pressure drops and maximize convective heat transfer coefficients);
- sufficiently high boiling temperature under atmospheric pressure to avoid a more stringent requirements for the selection of the condenser;
- must be chemical stable up to the highest expected operating temperature and pressure – under a high working parameters organic fluids tend to composite, resulting in

material corrosion and possible detonation; necessary select a chemically stable working fluids under working conditions;

- low both ODP (ozon depletion potential relative to R11) and GWP (global warming potential, relative to CO_2);
- a high flash point in order to avoid flammability;
- a low toxicity due to the personnel protection from the threat of contamination in case of a fluid leakage;
- low cost, essentially nonfouling, noncorrosive and among others.

Figure 7 presents designation and safety classification of refrigerants by ASHRAE standard.

The ideal working fluid, which simultaneously meets all of the requirements, do not exist. Real fluids must be screened to select primary candidate working fluids on a relative basis.

In the case of using geothermal heat source, the choice of working fluid can greatly affect the objective function which is a measure of geothermal power plant cost, sometimes the differences could be twice [14]. The high boiling working fluids as n-butane with overhanging saturated vapour line in subcritical cycle can achieve the highest thermal efficiency of 0.13 [28].

The effect of various working fluids on ORC performances is mainly investigated on low temperature heat sources as solar energy, biomass, waste heat and ocean energy [28-41]. Due to this paper deals with selection of most suitable fluids for low-temperature geothermal ORC.

Table 2 presents the working fluids whose potential for power production by means of ORC with low temperature geothermal source and summarizes their thermodynamic and physical properties. The molecular mass suggests the density of fluid; the critical point suggest the possible operating temperature and pressure range; ozon depletion potential (OZP), global warming potential (GWP) and the atmospheric lifetime (ALT) are the environmental aspects; the ASHRAE refrigerant safety classification indicates on fluid's level of danger.

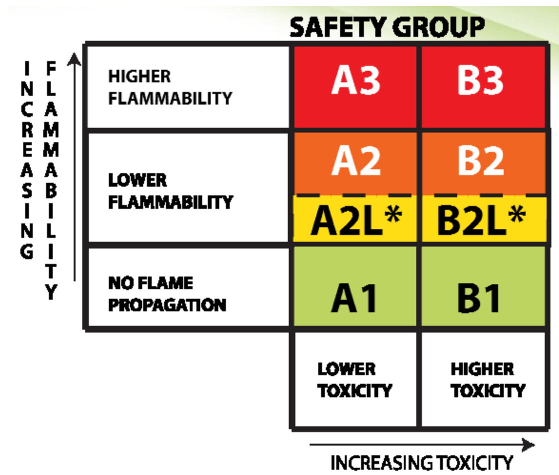

Figure 7 Designation and safety classification of refrigerants by ASHRAE standard

Table 2 Properties of the working fluids considered in this paper [28-41]

Working fluid		Physical data				Safety data - ASHRAE 34 safety group	Environmental data		
		Molecular mass [kg/kmol]	T_{bp} [°C]	T_{crit} [°C]	p_{crit} [MPa]		ALT [yr]	ODP [-]	GWP [100 yr]
1	R236fa	152.04	-1.4	124.9	3.65	A1	242	0	9820
2	toluene	92.14	110.6	318.6	4.13	n.a.	n.a.	n.a.	n.a.
3	R365mfc	148.07	40.15	186.85	3.266	n.a.	8.6	0	794
4	R236ea	152.04	6.2	139.29	3.502	n.a.	10.7	0	1370
5	C5F12	288	36.1	196.55	3.37	A3	0.009	0	20
6	hexane	86.18	68.71	234.67	3.034	n.a.	n.a.	n.a.	n.a.
7	R123	152.93	27.82	183.7	3.662	B1	1.3	0.020	77
8	R245ca	134.05	25.13	174.42	3.925	n.a.	6.2	0	693
9	R245fa	134.05	15.14	154	3.651	B1	7.6	0	1030
10	R21	102.92	8.86	178.33	5.181	B1	1.7	0.04	151
11	R114	170.92	3.6	145.7	3.257	A1	300	1	10,000
12	R113	187.38	47.6	214.1	3.392	A1	85	1	6130
13	R12	120.91	-29.8	112	4.14	A1	100	1	10,890
14	R11	137.37	23.708	197.96	4.4076	A1	45	1	4750
15	R152a	66.05	-24.02	113.15	4.52	A2	1.4	0	124
16	R142b	100.5	-9.12	137.11	4.06	A2	17.9	0.07	2310
17	R141b	116.95	32.05	204.35	4.212	A2	9.3	0.12	725
18	R600a	58.12	-11.7	134.7	3.63	A3	12±3	0	4
19	R600	58.12	-0.5	152	3.796	A3	12±3	0	3
20	R601a	72.1	27.8	187.2	3.78	A3	12±3	0	4±2
21	R601	72.1	32.0	204.2	4.249	A3	12±3	0.120	4±2

CASE STUDY – GEOTHERMAL POWER PLANT "BABINA GREDA"

The geothermal field at Babina Greda is situated in Vukovarsko-Srijemska County, in the municipalities of Babina Greda. The geothermal field has the reservoir depth 2500 m, with an average thickness 120 m. According to the categorisation of geothermal resources, the reservoir belongs to the lower temperature category [5].

The geothermal reservoir is a closed hydro-geological entity without natural replenishment, so it is expected that during exploitation, the exhausted geothermal fluid will be injected back into the reservoir to ensure the sustainability of the geothermal system. Based on proven features of existing wells drilled by INA (a Croatian oil company), there are two wells: the production well and the injection well [5]. The temperature at the mouth of the production well is 125 ºC, the pressure is 6 bar, and the flow is 100 l/s for a natural outflow [5].

In the proposed binary plant with the ORC geothermal fluid transfers heat to the working fluid by cooling from 125 ^oC to 69 ^oC. After that geothermal water will be used for direct usage, for heating of buildings, greenhouses, swimming pools, etc., if calculations show that this will not affect the production of electricity. Results of economic analyses usually favour combined heat and power generation [43].

Since at the location of the geothermal field Babina Greda the amounts of cooling water for the water-cooled condenser are not sufficient, the air-cooled condensers are used, whose thermodynamic calculations have been performed with the average annual air temperature of 15 ^oC. In thermodynamic calculations special attention is paid to the values of pinch point which is not below 5 ^oC.

The presumed isentropic efficiencies of turbine, pump and fan are 0.85 (dry turbine), 0.8 and 0.75.

Thermodynamic calculations for different working fluids from Table 2 are performed on a computer by means of mathematical model of ORC presented in one of the previous chapters. For ORC, an optimisation of the main cycle parameters is performed, i.e. of the cycle upper pressure, in order to obtain maximum cycle specific work (power) as it is described in [7]. Thermodynamic properties of working fluids are determined by REFPROP program [20].

The calculation results (performances) of ORCs for 21 working fluids from Table 2 are given in Table 3 [44].

Table 3 The calculation results (performances) of ORCs for selected working fluids from Table 2 [44]

Working fluid		Performances of ORC									
		Type	$\dot{W}_{net}$ [kW]	$\dot{m}_{wf}$ [kg/s]	η_{plant} [%]	$\dot{W}_t$ [kW]	$\dot{W}_p$ [kW]	$\dot{W}_f$ [kW]	$\dot{Q}_2$ [kW]	p_{max} [bar]	p_{min} [bar]
1	R236fa	dry	2415.00	120.68	10.95	2760.33	150.96	194.37	19,542.73	16.35	2.73
2	toluene	dry	2250.42	46.99	10.15	2448.76	2.35	195.99	19,716.90	0.32	0.04
3	R365mfc	dry	2309.09	89.62	10.42	2531.39	26.89	195.42	19,658.81	3.7	0.57
4	R236ea	dry	2382,76	112.52	10.75	2673.09	95.64	194.69	19,585.86	11.9	2.06
5	C5F12	dry	2198.01	151.80	9.92	2461.92	67.40	196.51	19,768.80	6.8	0.85
6	hexane	dry	2291.08	48.63	10.34	2497.00	10.33	195.59	19,676.64	1.4	0.20
7	R123	isentropic	2309.03	109.18	10.42	2539.93	35.48	195.42	19,658.87	4.8	0.91
8	R245ca	dry	2345.56	90.38	10.58	2583.54	42.93	195.06	19,622.70	6.0	1.01
9	R245fa	dry	2364.89	95.98	10.67	2622.15	62.39	194.87	19,603.56	8.6	1.48
10	R21	wet	2259.50	88.01	10.19	2503.81	48.80	195.90	19,707.91	7.8	1.82
11	R114	dry	2366.50	137.24	10.68	2660.85	99.50	194.85	19,601.96	10.6	2.14
12	R113	dry	2306.18	119.98	10.41	2521.12	19.50	195.44	19,661.69	2.6	0.45
13	R12	wet	2416.80	145.57	10.90	2907.75	296.60	194.36	19,552.16	27.8	6.51
14	R11	isentropic	2274.32	107.58	10.26	2506.39	36.31	195.76	19,693.23	4.8	1.06
15	R152a	wet	2414.36	74.88	10.89	2832.45	223.71	194.38	19,554.58	27.4	5.96
16	R142b	isentropic	2375.95	94.78	10.72	2691.55	120.84	194.76	19,592.61	14.9	3.38
17	R141b	isentropic	2283.67	84.92	10.30	2504.82	25.48	195.67	19,683.97	3.9	0.79
18	R600a	dry	2380.94	55.09	10.74	2718.89	143.24	194.71	19,587.67	15.2	3.51
19	R600	dry	2368.65	50.36	10.69	2656.65	93.17	194.83	19,599.84	10.9	2.43
20	R601a	dry	2308.69	51.34	10.42	2543.56	39.45	195.43	19,659.77	4.7	0.92
21	R601	dry	2307.70	48.92	10.41	2533.03	29.90	195.43	19,660.18	3.7	0.68

DISCUSSION

This paper presents comparison of 21 potential working fluid candidates for ORC with low temperature geothermal source, both on the basis of achieved plant thermodynamic performances (plant net power, mass flow rate of working fluid, plant efficiency, turbine, pump and fan work flow rate (power), rejected heat flow rate and upper and lower pressure of cycle) and their physical properties and environmental impacts.

From the results presented in previous chapter in Table 3, is visible that geothermal power plant with Organic Rankine Cycles with 21 selected working fluids whose properties are given in Table 2, achieves plant efficiency in range 9.92% to

10.95%. At the same time the plant net power with 21 selected working fluids is in the range 2198.01 kW to 2415.0 kW with the mass flow rates from 46.99 kg/s to 151.80 kg/s. Areas of the changes of turbine, pump and fan work flow rates are respectively: 2448.76 kW to 2907.75 kW; 2.35 kW to 296.60 kW and 194.37 kW to 195.99 kW. Important parameters of the cycle are the upper and lower pressure: the upper pressure changes in range of 0.32 bar to 27.8 bar, while the lower pressure in range 0.04 bar to 6.51 bar. The rejected heat from the working fluid to cooling fluid (air) changes in accordance with plant efficiency change.

When deciding which is the working fluid most suitable should be kept in mind the following facts.

The turbine size factor which takes into account turbine exit volume flow rate and enthalpy drop is an indicator of turbine size – it is proportional to actual turbine size [45].

Evaporator pressure (upper cycle pressure) is an important parameter for optimal power output and minimum heat exchanger area. Unfortunately, it is very difficult to choose working fluid which requires both minimum heat exchanger area and smallest turbine size factor [36].

Some authors [46] suggest that high latent heat, high density and low liquid specific heat are preferable, as a fluid with a high latent heat and density absorbs more energy from the source in the evaporator and thus reduces the required flow rate, the size of the plant, the pump consumption, while others [47] suggest that low latent heat is better because the saturated vapour at the turbine inlet would provide the best operating conditions.

Condensation is a necessary process in the organic Rankine cycle. The design condensation temperature is normally above 300 K in order to reject heat to the ambient. The critical point of a working fluid suggests the proper operating temperature rang for the working fluid of liquid and vapour forms, therefore the critical temperature is an important data for fluid selection [36].

Another important thermodynamic property is the freezing point of the fluid, which must be below the lowest operating temperature in the cycle. The fluid must also work in an acceptable pressure range. Very high pressure or high vacuum has a tendency to impact the reliability of the cycle or increase the cost [38].

Organic fluids usually suffer chemical deterioration and decomposition at high temperatures. The maximumm operating temperature is thus limited by the chemical stability of the working fluid [48].

The working fluid should be non-corrosive and compatible with engine materials [49].

The ODP and GWP represent substance's potential to contribute to ozone degradation and global warming.

On the basis ASHRAE refrigerant safety classification, characteristics as non-flammable and non-toxic are expected.

The availability and cost of working fluids are very important whwn selecting working fluids.

CONCLUSION

This paper investigates the potential of 21 different working fluids for power production by means of ORC with low temperature geothermal source – case study Geothermal Power Plant “Babina Greda”. ORCs with investigated working fluids have plant efficiency and plant net power in the range 9.92% to 10.95% i.e. 2198.01 kW to 2415.0 kW. In this respect, all working fluids are equally favorable, so it is necessary to set additional criteria such as the complexity and cost of plant and environmental impact.

So, the following fluids are not recommended:

- R21, R12 and R152a are wet fluids and expansion in turbine would cause wet steam problems (intensive erosion of turbine blades) or it is necessary to introduce steam superheating (incorporation of a superheater could bring additional cost);
- due to environmental concerns working fluids such as R114, R113, R12 and R11 have been phased out now while working fluids such as R123, R21, R142b and R141b are being phased out in 2020 or 2030 (high ALT, GWP and ODP);
- though the working fluids such as R236fa, toluene, R365mfc, R236ea, hexane, R245ca, R245fa and R152a are among the fluids with the highest plant efficiency and plant net power (with the exception of C5F12), however some of them have a high ALT or (and) GWP and high upper pressure or low lower pressure.

Concluding, R601a and R601 (low ALT, ODP and GWP, favorable upper and lower pressure) followed by R600a and R600 (low ALT, ODP and GWP, higher upper and lower pressure) are most suitable fluids for ORCs with low-temperature geothermal sources.

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