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Optimization of Olkaria Geothermal Brine for a Proposed Binary Unit by Energy and Exergy Analysis

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ABSTRACT

The paper presents the best working fluid to optimize the geothermal resource of Olkaria complex geothermal field in Kenya. The reinjected brine at 156°C with 206 kg/s is used to model, design and optimize basic binary unit using Engineering Equation Solver (EES) code for different working fluids. System optimization defines the guidelines in selection of working fluid and the configuration of the power plant. The objective functions of the paper were to optimize the system to get the highest power output. The design is constrained by the available separator parameters, by application of the first and second laws of thermodynamics. The power generation output from Olkaria II unit will have additional power to supply to the national grid. For the different working fluids studied the least power that can generated is 3,794 kWe using R152a fluid with the highest being application of R600a, 6,792 kWe. Addition of power from renewable source will also reduce the effect of CO_2 emissions. Energy and exergy analysis is a powerful tool in decision making in power plant designs.

1. INTRODUCTION

Geothermal energy is available anywhere in the earth's crust [1, 2]. Geothermal energy utilization is mainly power conversion technologies as flash or binary cycles [3]. In Kenya most of the units operating are single flash developed in Olkaria geothermal complex along the East Africa Great Rift Valley. This paper optimizes the geothermal energy available in Olkaria II geothermal power plant in Kenya. The reservoir temperature estimates are 375o C [4]. Most of the geothermal resources in the world; about 70% are estimated to be lower than 150o C [10, 11]. Geothermal resources with temperatures less than 150oC are best utilized for binary units [1, 13, 14]. Geothermal energy outranks other renewable energy sources environmentally and economically [9]. Injected water temperatures vary between 70-80 ◦ C for geothermal power plant in Turkey [10, 12]. The cycle operating parameters are usually optimized and selection of most suitable working fluid [7]. Selection of working fluids is influenced by many factors; thermodynamics and environmental effects. Critical pressures and temperatures are the key parameters in ORC cycle and are usually correlated to the available geothermal fluid temperatures.

Olkaria II single flash units generate 105 MW from 3 condensing turbo-generating units of each 35 MW [11]. In Olkaria II power plant two phase fluid is separated in the separator at 462.25 kPa, 156.4o C into brine and steam. The steam quality is 0.5236 and flow rate of 227.4 Kg/s while the brine flow rate is 206.9 Kg/s. The brine re-injected at this state has energy and exergy that can be further utilized for power generation in a binary unit. From the data available that was used is this paper, the brine exergy at separator exit is 21.5 MW of 196.62 MW exergy into the separator. Other parameters are; condenser (temperature, 44.97o C, pressure, 699.7 kPa, condensate, m ̇_cs, 2372 kg/s, cooling water, m ̇_cw, 2194 kg/s) [11]. The ORC cycle for different working fluids in this study is optimized. Turbine network, efficiencies and parasitic loads are taken into consideration.

2. BINARY POWER PLANT AND ENERGY ANALYSIS

Binary cycle converts thermal geothermal heat into mechanical energy in turbine that is then converted to electricity by generator; unlike conventional power plants, they do not have boiler [22, 23]. Low-medium temperature geothermal sources have potential as a renewable source of energy but with low efficiencies; less than 12% [11, 25]. For better electricity conversion efficiency for low temperature geothermal sources, binary cycles are used [15]. The first binary geothermal plant used ethyl chloride (C2H5Cl) as working fluid [1]. Heat was supplied with two phase brine (27.8 kg/s steam and 18 kg/s water) at 130o C from a single well with estimated values of 250 KW and 12.4% thermal efficiency [1]. Geothermal binary units contribute for 73% of ORC cycles [12]. The heat source temperature may vary from as low as 50 o C to 250 o C [16]. Flow rate of 69 l/s with temperatures of 60-170 o C developed in Tibet region generate 1 MW in remote area. Binary power plants constitute over 35% of the geothermal units as of December 2014 with average rating of 6 MW per unit [1].

Suitable working fluid receives heat from brine in evaporator, expands in turbine, condenses and pumped to evaporator by feed pump [1, 19]. Organic Rankine Cycle (ORC) convert thermal energy as low as 80o C [14, 22, 27]. Source of geothermal water can be the geothermal fields of abandoned oil well as in Nevada, where 92o C fluid at a flow rate of 26 kg/s generate 216 kW [19]. Huaibei Oil field, has the first ORC system in China with 110o C of geothermal fluid [19]. For small binary units, they can be easily transported to remote locations and size scaled based on the temperature and flow rate of the available geothermal fluid [18]. Binary units are cost effective for the low enthalpy resources [20].

Heat exchangers (evaporator and preheater) play a major role in binary units because they are in contact with heat source (hot brine) [21]. They transfer energy between surfaces should be designed to optimize the transfer rate [22]. The general steady state energy balance equation for any components are as shown in equations 3 and 4 [13, 31].

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \quad (1)$$

$$\dot{Q} - \dot{W} + \sum \dot{m}_{in} h_{in} - \sum \dot{m}_{out} h_{out} = 0 \quad (2)$$

The energy efficiency of the system is calculated as follows:

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} \quad (3)$$

Binary plants have efficiencies between 6.362-15.35 % [15]. Dry fluids are more efficient than wet-fluids [15].

3. SYSTEM DESCRIPTION AND THERMODYNAMIC ANALYSIS

The proposed additional model for the Olkaria II is basic binary power plant (Figure 1) [1]. Single flash power plant units have been in operation thus the reservoir is capable of sustaining operations for many years. Addition of the binary unit will increase the power output and efficiencies of the available geothermal energy in Olkaria II [12]. To model any given power plant unit, the main parameters known are flow rate (m ̇) and temperature of the brine. Other useful thermodynamic properties are obtained from steam tables or EES code. For any thermodynamic system, the energy, mass and exergy balance equations hold.

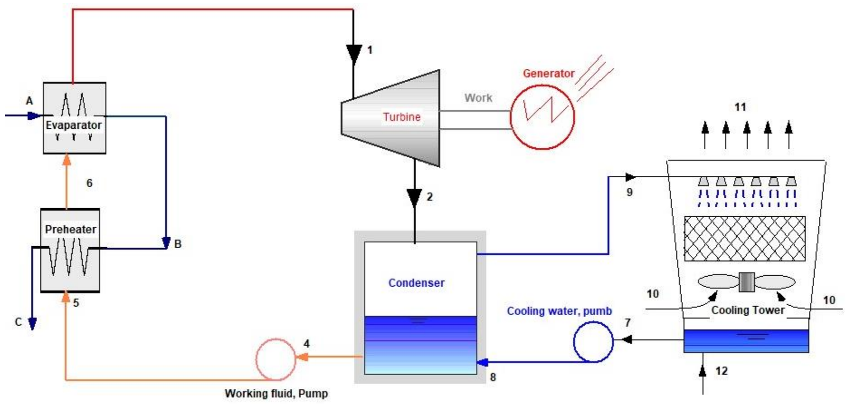

Figure 1: Proposed basic binary unit designed using EES code.

The geothermal brine (State 2) from the separator enters the ORC binary evaporator at 156.7oC. Working fluid enters the preheater and evaporator (States d and e respectively) and is changed to saturated or super-heated vapor (State a). For an optimization pressure; P3, the vapor expands isentropically in the turbine coupled to a generator. From literature the condenser temperature, T c is set at 46.5o C [1, 31]. At State c the sub-cooled fluid is pumped to the preheater and evaporator to complete the closed loop of ORC.

Table 1: Common operating conditions for the system.

Parameter	Value
Brine mass flow rate (brine)	206 kg/s
Heat exchangers pinch point (T_{pp})	8^{o} C
Turbine isentropic efficiency (η_{tur})	85%
Pumps isentropic efficiency (η_{pump})	75%
Ambient pressure (P_0)	86 kPa
Ambient temperature (T_0)	293.15 K

The important factor in binary power plant is working fluid selection. Working fluid, in most cases organic compounds or mixture affects the performances of binary plants [1]. Its selection is constrained by thermodynamic properties; critical temperature, Tcr and critical pressure, Pcr, health, safety and environmental impacts [1, 14, 35]. Table 2 shows some of the working fluid properties [1 ,22, 35, 36].

Table 2: Properties of some candidate working fluids for binary.

Fluid	*Formula*	*T_{cr} (ºC)*	*P_{cr} (kPa)*	*ODP*	*GWP*	*Flammability*	*Toxicity*
Ammonia	NH_3	133.7	11.7	0	0	Lower	Toxic
i-Butane	i- C_4H_{10}	136.0	3.7	0	3	Very high	Low
n-Butane	C_4H_{10}	150.8	3.7	0	3	Very high	Low
i-Pentane	i-C_5H_{12}	187.8	3.4	0	3	Very high	Low
Carbon dioxide	CO_2	-	-	0	1020	Non	Non
Water	H_2O	374.1	22.1	0	-	Non	Non

Working fluids are classified as wet, isentropic or dry as shown depending on the shape of the T-s diagram on the vapor line [18, 26]. The type of the working fluid will influence the binary geothermal layout, performance and exergy efficiencies [29, 24].

The temperature of the brine/source dictates the fluid to be selected. Brine in this paper has a temperature of 156o C, thus the working fluid suitable for ORC unit will have at least Tc ≤ 142oC [1]. Performance of binary cycles is not affected by NCG contained in primary geothermal fluid [25]. World's energy resources are limited thus the need for detailed studies to eliminate wastage [30]. To clearly understand the exergy and energy concept, key thermodynamic property is entropy which takes into account the effects of irreversibility in a system. Alternative sources of energy especially renewable energy sources are being developed in various parts of the world [31].

Exergy is the available energy that is available from a system when a system interacts to equilibrium with the surrounding environment [30, 37, 42]. It can be defined also as the amount of work that can be obtained from energy using the surrounding environment as the heat and matter reservoir. Exergy's goal is to maximize/optimize available energy for better utilization [41, 43]. Exergy analysis is used to identify system's inefficiency in terms of exergy destruction for the components in respect to its surrounding attributing to more sustainable technologies [31, 40, 41, 44, 45]. It is based on the first and second laws of thermodynamics and important tool for designing of thermal systems [30, 46]. Exergy models show the imperfections in thermodynamic processes and helps to make complex thermodynamic models more efficient [42, 47]. It is also described as a measure for identifying and explaining sustainable energy (equation17) [43, 45].

$$e = h - h_0 - T_0(s - s_0) \tag{4}$$

Thermo-mechanical exergy is considered where the kinetic, potential and chemical energies are not considered [30]. Exergetic power input, output and exergetic accounting equations are given by equations 5, 6 and 7respectively [1];

$$\dot{E}_{in} = \dot{E}_Q + \sum_{i=1}^{k} \dot{m}_i e_i \tag{5}$$

$$\dot{E}_{out} = \dot{E}_W + \sum_{j=1}^{k} \dot{m}_j e_j \tag{6}$$

$$\Delta\dot{E} = \dot{E}_{in} - \dot{E}_{out} = \dot{E}_Q + \sum_{i=1}^{k} \dot{m}_i e_i - \dot{E}_W - \sum_{j=1}^{k} \dot{m}_j e_j \tag{7}$$

where i, is for all incoming streams and j for all outgoing streams with the exergy loss, $\Delta\dot{E}$ is always positive [1].

Utilization/ exergetic (η_u) and second utilization (η_{u2}) efficiencies are calculated as:

$$\eta_u = \frac{\dot{W}_{net}}{\dot{E}_{in}} \tag{8}$$

$$\eta_{u2} = \frac{\dot{W}_{net}}{\dot{E}_{available}} \tag{9}$$

Pinch point temperature difference (PPTD) affects the thermodynamic and economic performance of heat exchangers [7]. The pinch point for the heat exchangers is 8o C. Using equations 18 and 19 and pinch point, preheater exit temperature/reinjection temperature is calculated by EES code [1].

$$\dot{m}_{brine}c_{brine}(T_A - T_B) = \dot{m}_{wf}(h_1 - h_6) \tag{10}$$

$$\frac{T_A - T_C}{T_A - T_{AB}} = \frac{h_1 - h_5}{h_1 - h_6} \tag{11}$$

Optimization of the modeled plant is a complex multiobjective and multivariable constrained problem [19 ,24, 52]. Many thermodynamic parameters are input into EES code. The fixed parameters are brine temperature and flow rate and ambient conditions of the region. Most of the other specifications like, turbine pressure [39] and temperatures were arrived at from simulation results of the EES code. For the heat exchangers analysis, mass and energy balance equations (equations 10 and 11) are used. In each of the heat exchangers applied, pinch point of 8oC was used [1, 24]. Performance of ORC can be optimized based on heat exchangers surface area, varying pressures and temperatures of turbine and condenser [24]. Temperature of geothermal fluid to be reinjected can be fixed not to be less than 70o C [12, 31].

The model was optimized based on maximum network, optimum turbine pressure, reinjection temperatures above 70o C and highest efficiencies for different working fluids.

Chlorofluorocarbons have good thermodynamic properties but releases chlorine which catalyze the destruction of ozone layer. The suitable alternatives for CFC's are hydrofluorocarbons (HFC's) having proper precautions in place to avoid environmental damages and harming human health [12]. Hydrocarbons saturated with fluorine tend to be stable in presence of iron, steel and copper [25]. From the list of working fluid in Table 2, the fluids considered for the binary plant are butane, ammonia, and isobutane. Other fluids not in the Table 2 identified by the EES code analyzed include; trans2butene, isobutene, R600a, R152a and R236ea. EES code is used to get the thermodynamic parameters of the fluids. The different working fluids analyzed in this paper were in agreement with the constraining energy and mass balance equations [1].

4. RESULTS

In this paper effects of different working fluids in simple binary geothermal power plant were investigated. Selection of the working fluid affects the performance of the plant as presented in this section. In the study eight working fluids were selected based on the validity of the energy and mass balance equations in the heat exchangers (evaporator and preheater using equations 18 and 19) with same pinch point.

The required temperature varies for each working fluid. The working fluids are expanded in the turbine by varying pressures close to Pcr [26]. The brine reinjection temperature was to be above 70o C [7, 10]. Heat transfer in the preheater and evaporator for the different working fluids shows that the best pinch point is 8o C. For the working fluids investigated the turbine operating pressure, P1, is less than the critical pressure. Pressures lower than critical ensures the steady operating conditions of the system/plant. The eight different working fluids investigated have reinjection temperature, TC above 70 ◦ C [14].

Table 3: Optimized model for different working fluids.

Fluid	P_1 (kPa)	P_{cr} (kPa)	T_C (ºC)	W_{net} (kW)	Sum_{exd} (kW)	η_{th} (-)	η_u (-)	η_{u2} (-)	$\dot{m}$ (kg/s)
Ammonia	6,119	11,333	88.04	5,984	7,601	9.902	29.94	40.31	58.3
Isobutane	2,394	3,640	81.02	6,791	7,562	10.35	34.5	43.44	176.9
Isobutene	2,000	4,010	83.37	6,461	7,654	10.16	32.82	42.21	159.9
Trans2butene	2,000	4,027	99.14	5,790	5,972	11.67	29.41	45.18	115.4
Butene	1,909	4,005	84.33	6,343	7,656	10.11	32.22	41.81	158.4
R600a	2,356	3,640	80.41	6,792	7,646	10.27	34.51	43.22	178.5
R152a	3,667	4,520	90.00	3,794	9,748	6.561	19.27	26.50	324.2
R236ea	1,800	3,429	78.51	6,750	8,014	10.02	34.29	42.44	376.1

From Table 3 the lowest preheater brine exit temperature is 78.51 ◦ C for R236ea working fluid. The highest TC, 99.14o C is noted in the Trans2butene working fluid. Higher exergy losses in the evaporator is due to the large temperature difference. For less exergy losses in the heat exchangers, especially evaporator, compressed liquid should be heated to supercritical vapor.
Of the eight working fluids studied; highest turbine network was generated by a system with R600a fluid; 6,792 kW. Isobutane have similar results with a difference of only 1 kW of network. Ammonia has the highest turbine pressure at 6,119 kPa with the lowest being R236ea, 1800 kPa.

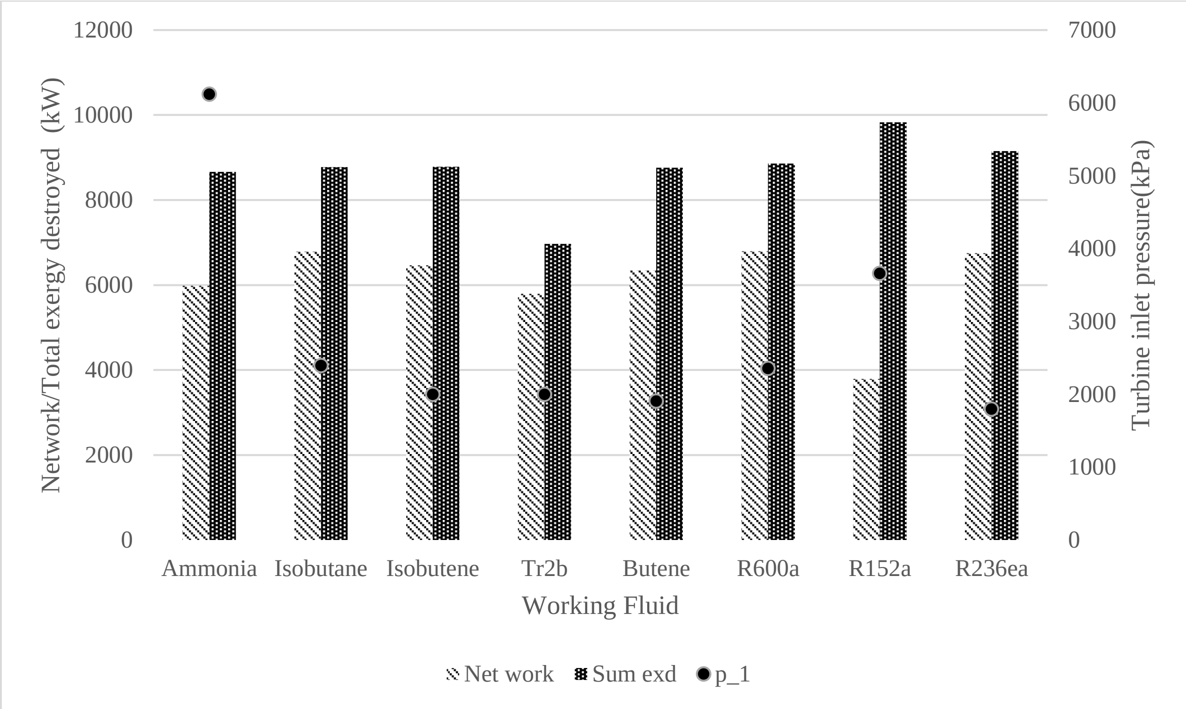

Figure 2: Relationship of network generated, summation of exergy destroyed and turbine inlet pressure for different working fluid.

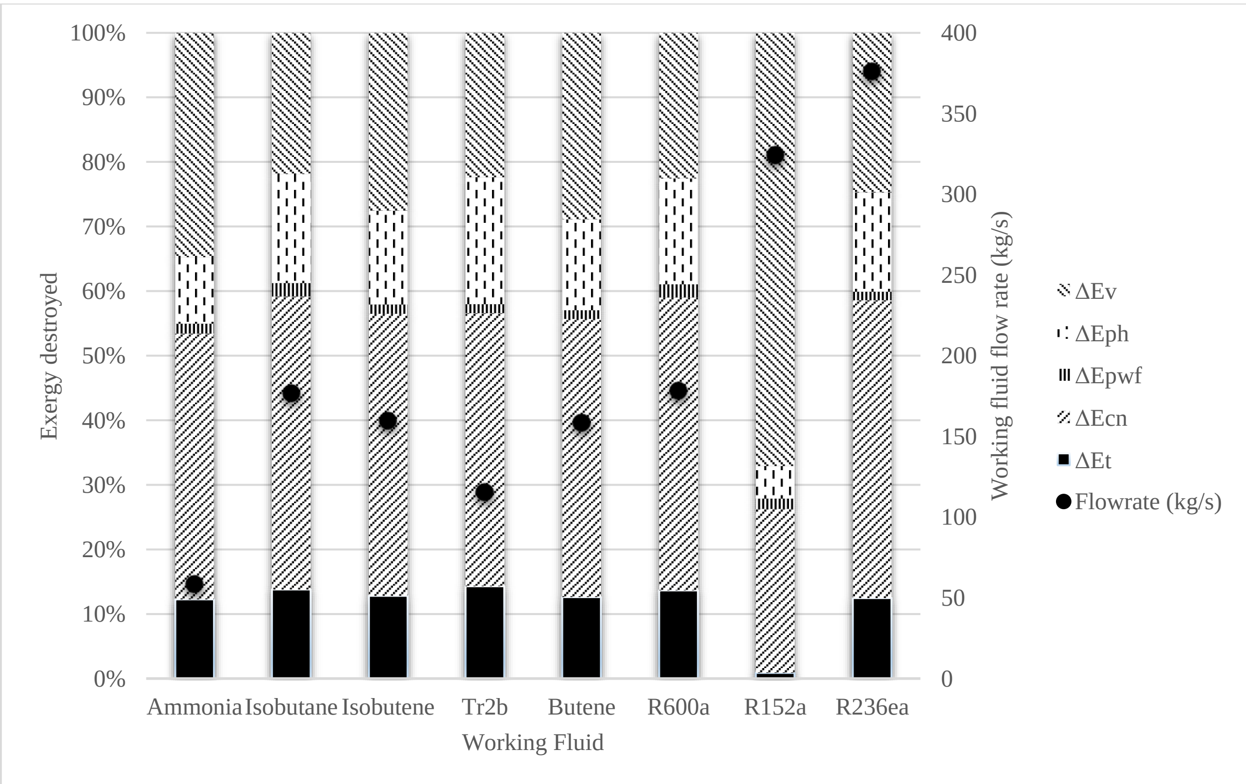

Figure 3: Relationship between exergy destroyed and flow rates of different working fluids. Most of the exergy losses are in the heat exchangers sections/states.

5. CONCLUSIONS

The following conclusions can be drawn from this research:

Binary plants have low efficiency as compared to single flash and double flash. Highest exergy destruction for different working fluids is in the condenser, while the least is in the working fluid pump. All the heat exchangers contribute to the highest exergy destruction.

Depending on the optimization objective, different working fluids can be best suited for the ORC plant. On the objective of the most efficient and highest reinjection temperature working fluid, trans2butene has ηth of 11.67 %, ηu of 29.41% ηu2 of 45.18 and TC at 99.14 ◦ C. The other objective that is considered for the different working fluids in the turbine inlet pressure, P1, and the working fluid identified with the least pressure is R236ea. Dry fluids are more efficient than wet fluids.

The results of this study prove that selection of the working fluid for ORC is multiobjective and depend on number parameters (turbine inlet pressure, efficiencies, maximum power generated, reinjection temperature of geothermal fluid). Retrofitting of ORC unit to maximize the available exergy in Olkaria II has a potential of generating at least 3,394 kWe and at highest 6,792 kWe in addition to the SF 105 MWe.

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