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Comparative Analysis of Low Global Warming Working Fluids for Geothermal-Solar Hybrid Cycle

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***Abstract*—** Low quality brine discharged from the separator at Olkaria II power plant is normally reinjected back into the ground. Utilizing waste brine in an organic rankine cycle technology can result in cycle efficiency of around 12%. The efficiency can further be improved by the integration of parabolic trough collector to the geothermal cycle. Previous studies on geothermal-solar hybrid cycles have been analyzed using higher global warming potential working fluids such as R134a and R245fa. These organic working fluids pose danger to the environment and contravene protocols such as the Montreal Protocol, Kyoto Protocol and Paris Agreement which insist on the substitution of harmful substances that are accelerating global warming. In this study R-600a (isobutane), R-290 (propane), R-1150 (ethylene) and R152a (difluoroethane) which are low global warming potential organic working fluids are analyzed in terms of pump power, power output and net power output using geothermal-solar hybrid cycle for waste brine at Olkaria II power plant in Kenya. The results obtained show that R1150 produces the highest power output and net power followed by R290, R152A and R600A.

***Keywords*—** Organic Rankine cycle, Parabolic trough, Global warming potential, Cycle efficiency.

I. INTRODUCTION

DUE to an increase in world population, the world is facing high energy demand. The current rise in energy consumption is triggered by more energy demand in the construction, transportation and manufacturing sectors. Considering Africa, majority of the nations are developing with high population growth rate and soaring energy demand. To meet the rising energy demand, strategies need to be put in place on power generation from sources that have minimal impact on the environment. In Kenya, for example, power is mainly generated from renewable sources such as geothermal, hydro, wind and solar. Amongst these, geothermal has a big share of power generation at 41% of all electricity supplied in Kenya [1].

Considering Olkaria II geothermal power plant, approximately 105 MW of electricity is generated [2]. However, the discharged brine from the separator is not reutilized for power generation. Instead, most of it is reinjected back into the ground as illustrated in Figure 1. According to Nyakundi et al. [3], the separated brine has extractable energy of about 417 kg/s which is currently re-injected back into the ground. There are studies that have been conducted on using Organic Rankine Cycle (ORC) to utilize this brine for power generation. However, the efficiency of the system was reported to be around 12 %. The efficiency can be improved by using a geothermal-solar hybrid system. This principle can also be applied to low temperature geothermal hot spring.

Alibaba et al. [4] investigated R113, R114, R132, R236a and R134a working fluids in terms of exergetic, economic and environmental performance for hybrid Geothermal–Solar power plant. R114 working fluid was thermodynamically appropriate, thus it was selected as the working fluid. Their study used higher Global Warming Potential (GWP) which has a negative effect to the environment.

Qyyum et al. [5] evaluated ORC systems, facilitated by biogas combustion flue gases, using n-butanol, i-butanol, and methylcyclohexane, as working fluids technically and economically, from a process system engineering perspective by using the Aspen HYSYS R V10 software. The performance of the mentioned working fluids was compared with that of toluene and the results show that i-butanol and n-butanol are the most competitive alternatives in terms of work output, exergy efficiency, thermal efficiency, total annual cost, and annual profit. The study concluded that i-butanol and n-butanol are promising working fluids for high-temperature ORC systems. They did not investigate the effect of working fluid pump power required as well as the effect of varying the organic working fluid mass flow rate on power output as it is going to be investigated in this research.

Baral [6] performed the feasibility of stand-alone hybrid geothermal-solar ORC technology for power generation from hot springs of Bhurung Tatopani, Myagdi, Nepal using R134a and R245fa working fluids. The results showed that 1 kg/s of working fluid could produce 17.5 kW and 22.5kW power output for R134a and R245fa respectively when the geothermal source temperature was around 70 °C.

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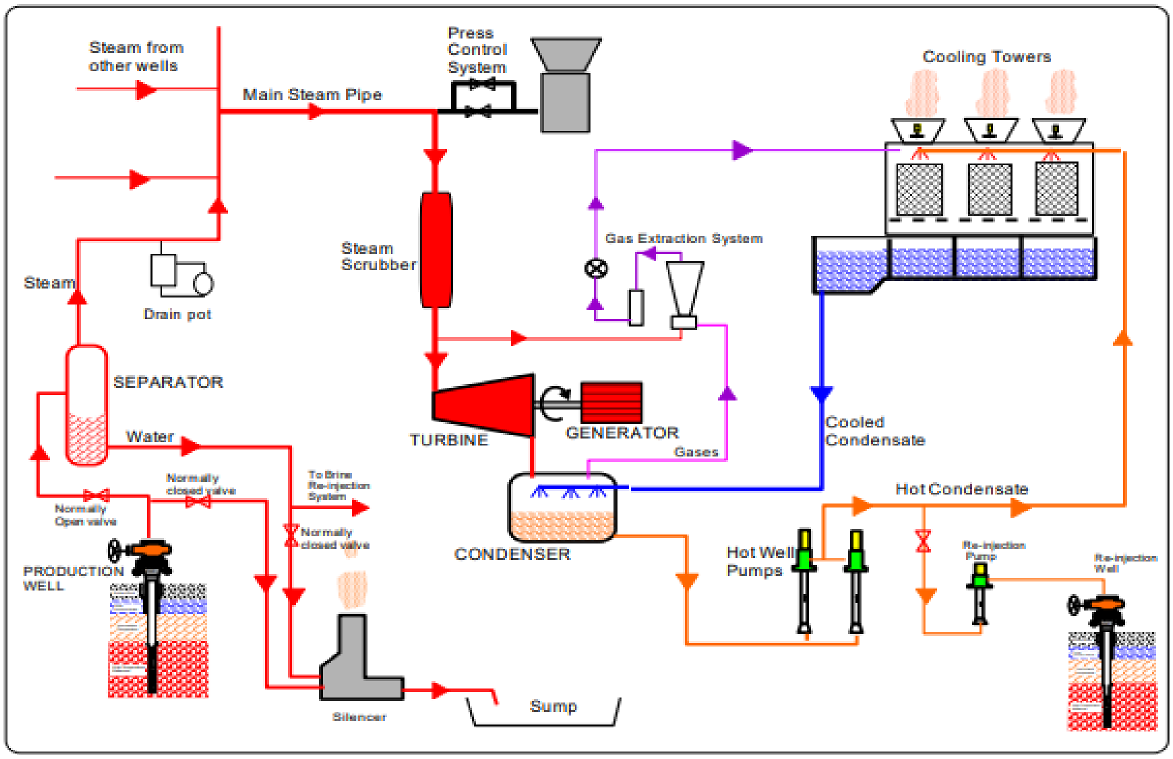

Figure 1: Olkaria II Power station process diagram [7]

Further, the results showed that when the temperature was raised to 99 °C by using a flat plate solar collector, the power outputs were increased to 25 kW and 30 kW for R134a and R245fa, respectively. In this research, geothermal-solar hybrid system is studied. A parabolic trough solar collector is selected over a flat plate collector to achieve higher heating of the waste brine. A parabolic solar collector uses rows of parabolic cylinder-shaped mirrors. A pipe passes through the parabola's focus that receives the concentrated rays of the sun, where the Therminol VP1 fluid is heated to a temperature of 400 °C. Therminol VP1 fluid is heating the brine through the heat exchanger.

Four organic working fluids, i.e. R1150, R290, R152A and R600A are compared in terms of pump power, power output and net power output through Aspen HYSYS V11 simulation.

The selected organic working fluids have a low Global Warming Potential (GWP) and zero Ozone Depletion Potential (ODP). According to the international protocols such as the Montreal Protocol, Kyoto Protocol and Paris Agreement, the organic working fluid, must have zero ODP and low-GWP (lower than 150) [8]–[10].

II. METHODOLOGY

A. Process Simulation

The process simulation was performed in Aspen HYSYS V11 as shown in Figure 2. The model consists of Solar Heat Transfer (SHT) loop, Geothermal Brine Loop and Organic Fluid Loop. For the SHT, the working fluid used is Therminol VP-1 [11], [12]

The brine from the separator at Olkaria II power plant has a temperature, pressure and flow rate of 158.9°C, 6 bar and 157.22 kg/s respectively [13]. These are the inputs in the system for stream Geothermal brine in.

In this system, the geothermal waste brine from the separator is passed through the Brush heat exchanger (BHX) where it is heated by solar fluid from the parabolic trough solar collector. The heated brine is getting separated into the hot brine and the superheated steam which drives the steam turbine. The saturated steam leaving the steam turbine is transferred through the Low Temperature Heat exchanger (LTH) where it heats the organic fluid and then sent back to the reinjection well. The Organic fluid is also getting heated by the hot geothermal brine coming from the separator before the steam turbine through the High Temperature Heat exchanger (HTH). The organic fluid produces the steam after getting heated and drives the Binary Turbine (BT).

Therminol VP1 fluid was heated to a maximum temperature of 400 °C. The mass flow rates of the organic working fluids were varied from 200 kg/s to 400 kg/s and the pump power, power output and net power output were investigated. The flash hybrid cycle used in this study is similar to the one that was used by Greenhut et al [11]. It is selected because it produces more power output as compared to other hybrid cycle such as superheat hybrid.

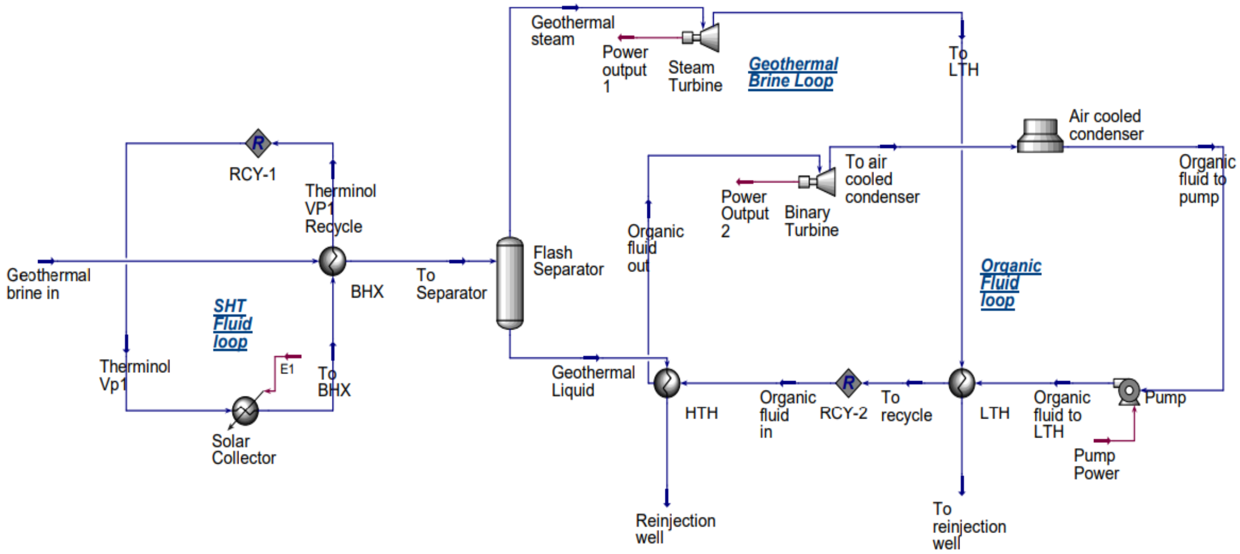

Figure 2: Geothermal-solar hybrid Model in Aspen HYSYS

B. General Assumptions and Equations

The following general assumptions are made:

All the components and processes are considered to be at steady state. The heat and pressure losses in all system components and piping are neglected. The turbine and pump are adiabatic with 85% isentropic efficiencies. This is the preferred isentropic efficiency for ORC system components [11], [14]. The changes in kinetic and potential energy are not considered. Those are the assumptions that are commonly used in the steady state process simulation [5], [11], [15].

The general steady state energy balance equation, based on the first law of thermodynamics, can be written as follows:

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

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

Where Q and W represent the heat transfer and work energy crossing the component boundaries and $\dot{m}$ and h respectively represent the mass flow rate and the specific enthalpy of the streams of the system working fluid.

The net work (W_{net}), Turbine work ($W_{Turbine}$) and the pump work (W_{pump}) are given by the formulas as shown below:

$$W_{net} = W_{Turbine} - W_{pump} \qquad (3)$$

$$W_{Turbine} = \dot{m}_f \, (h_i - h_{out}) \qquad (4)$$

Where, $\dot{m}_f$, h_i and h_{out} are the mass flow rate and enthalpy at specific pressure and temperature at the inlet and outlet of the turbine, respectively.

$$W_{pump} = \frac{\upsilon_p \, (P_o - P_i) \times \dot{m}_f}{\eta_p} \qquad (5)$$

Where P_o and P_i denote the pressure at the outlet and inlet of the pump, respectively. $\dot{m}_f$, η_p and υ_p are the mass flow rate of the working fluid, efficiency of the pump, and specific volume of the fluid, respectively.

C. Working Fluid Selection

The working fluids were selected based on their thermodynamic properties, health and safety, economic and environmental considerations. The working fluids analyzed in this study are as presented in Table I. Working fluids are classified as dry, wet and isentropic. The difference is that the dry fluids have a positive slope; wet fluids have a negative slope and isentropic fluids have a vertical slope.

The isentropic working fluids are not considered in this study because they are phasing out due to their higher GWP. This research only focuses on dry and wet working fluids with a GWP less than 150. The working fluids have the following thermodynamic properties: high density, low Normal boiling Point (NBP), high moderate Critical Temperature (TC) and Critical Pressure (CP).

According to ASHRAE safety group the working fluids can also be grouped in terms of safety where letters A refers to “lower” toxicity while the letter B means “higher” toxicity and the numbers 1, 2 and 3 refer to flame propagation, number 1 means no flame propagation, number 2 means lower flammability and number 3 means higher flammability [16], [17]. The working fluids analyzed in this research are low toxic.

TABLE I: PROPERTIES OF ORGANIC WORING FLUIDS ANALYZED USING GEOTHERMAL-SOLAR HYBRID CYCLE [8], [9], [16], [20].

Working Fluid	NBP (ºC)	TC (ºC)	PC (kPa)	ASHRAE SAFETY GROUP	ODP	GWP (100 years)	Expansion	Density (kg/m^3)
R-600a	-11.7	135	3647	A3	0	3	dry	224.4
R-290	-42.1	96.68	4247	A3	0	3	wet	220.5
R-1150	-109.4	9.05	5040	A3	0	4	wet	567.9
R152a	-24	113.3	4520	A2	0	18	wet	368

III. RESULTS AND DISCUSSIONS

The results of the pump power, power output and net power output were compared for the working fluids in Table 1. Figure 3 shows that the organic working fluids mass flow rate and pump power are directly proportional. R1150 uses more pump power as compared to other working fluids. It is followed by R290, R152A and R600A. R600A uses the least pump power. This is in agreement with Borsukiewicz-Gozdur [18] work, who found out that pumping power decreases for the working fluids that have higher critical temperature. In this research it can be clearly seen in Table 1 that R1150 has lowest critical temperature as compared to other working fluids.

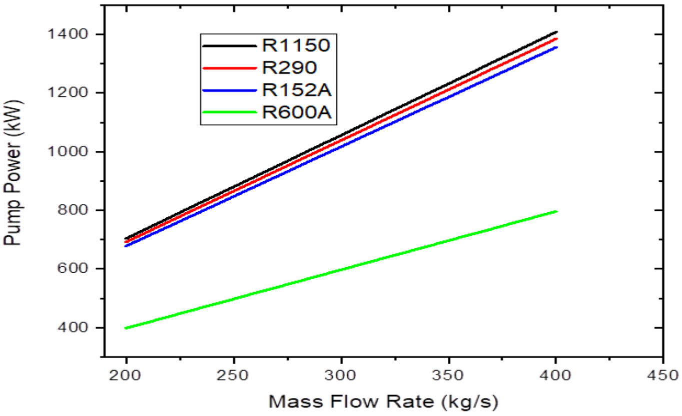

Figure 3: Comparison of the Pump power versus mass flow rate.

Figures 4 and 5, show that the power output and net power output are directly proportional to the working fluid mass flow rate. This is because when the mass flow rate increases the degree of superheat of the working fluid increases. Therefore, the working fluid absorbs more heat through the heat exchanger which results in more power output. R1150 produces the highest power output and net power followed by R290, R152A and R600A, respectively. R1150 produces more power because it has low critical temperature and low boiling point compared to other working fluids as per Table I The trends of the results are in agreement with the results obtained by Liang and Yu [19] and Rajabloo [14].

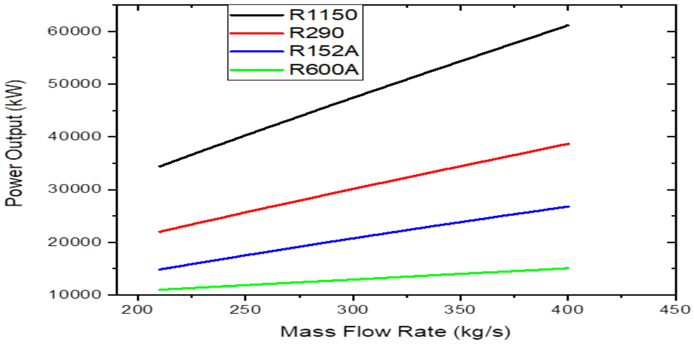

Figure 4: Comparison of the power output versus mass flow rate.

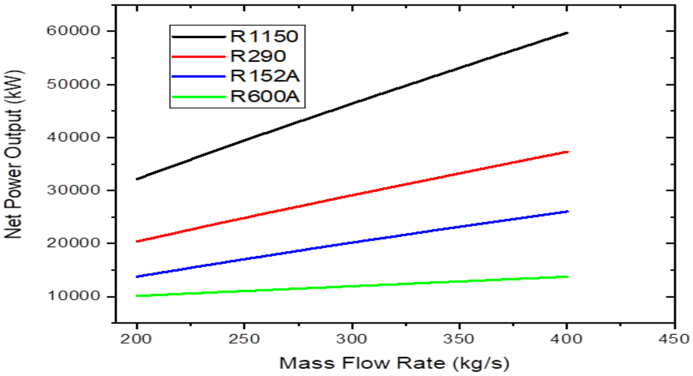

Figure 5: Comparison of the Net power output versus mass flow rate.

IV. CONCLUSION

R1150 is leading in power output and net power as compared to R290, R152A and R600A. This means that R1150 requires less mass flow rate in order to produce more power as compared to the other working fluids for the geothermal-solar hybrid power plant in Kenya. Selection of working fluid involves a number of factors therefore R290, R152A and R600A might be the best in other factors compared to R1150. For example, if you vary the geothermal source temperature, flow rate and pressure, working fluids might perform differently. Therefore, these results are only based on the conditions of waste brine at Olkaria II power plant and on the environments surrounding the power plant.

This study was only based on comparative analysis of working fluids in terms of power output, net power and pump power output, therefore in future the above working fluids should be analyzed fully for the whole year considering irradiance of different locations. The economic analysis of this hybrid system also needs to be performed in order to see if it is economical viable. Furthermore, studies need to be performed on working fluids mixture in order to improve the efficiency and properties of working fluid.

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