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SENSITIVITY ANALYSIS OF A SOLAR ORGANIC RANKINE CYCLE

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ABSTRACT: The solar organic rankine cycle is a promising technology which uses energy from the sun as a source of power and this does not affect the environment. However, due to the recent global warming, environmental pollution and energy crises coupled with the instability of oil prices, interest in renewable energy for mitigating these issues is growing once again. The aim of this study is to carry out a thermodynamic and sensitivity analysis of the system

A thermodynamic analysis was carried out to see how feasible the power plant will operate on the chosen site, simulation were done in a Matlab environment, parametric and sensitivity analysis were also carried out to know the parameters that effect the system the most.

The organic rankine cycle efficiencies and the overall solar organic rankine cycle efficiencies using R134a are 0.093, 0.086, 0.077 and 0.000028, 0.000030, 0.000032 respectively. The organic rankine cycle efficiencies and the overall solar organic rankine cycle efficiencies using R245fa are 0.200, 0.185, 0.167 and 0.000060, 0.000065, 0.000069 respectively.

Keywords: Efficiency, Net Power Output, Solar Organic Rankine, Thermal Energy.

1. INTRODUCTION

Since worldwide energy demand has been rapidly increasing but the fossil fuel to meet the demand is being drained, for the past 20 years efficient uses of low-temperature energy source such as geothermal energy, exhaust gas from gas turbine system, biomass combustion, waste heat from various industrial processes and solar energy have attracted much attention and researches about them become more and more important. The organic Rankine cycle (ORC) and the power generating system using binary mixture as a working fluid have been focused as they are proven to be the most feasible methods to achieve high efficiency in converting the low-grade thermal energy to more useful forms of energy. ORC is a Rankine cycle where an organic fluid is used instead of water as working fluid. Particularly in low temperature applications many benefits may be obtained by using ORC instead of steam Rankine process [2].

Energy is one of the primary causes of a nation's development and sustenance. It has been reported that the global demand for primary energy is on the steady increase and if the demand is maintained at a conservative average rate of 2%, the total global energy demand will increase by 100% in 30 years. The accelerated consumption of fossil fuels, if not abated would lead to a major health and energy crisis. However, the utilization of low-grade energy has attracted appreciable attention due to its potential in relaxing environmental pollution and fossil fuel consumption [1].

Worldwide energy demand has been rapidly increasing but the fossil fuel to meet the demand is being drained, for the past 20 years efficient uses of low-temperature energy source such as geothermal energy, exhaust gas from gas turbine system, biomass combustion, waste heat from various industrial processes, and solar energy have attracted much attention and researches about them become more and more important. The organic rankine cycle (ORC) and the power generating system using binary mixture as a working fluid have been focused on as they are proven to be the most feasible methods to achieve high efficiency in converting the low-grade thermal energy to more useful forms of energy. ORC is a rankine cycle where an organic fluid is used instead of water as working fluid. Particularly in low temperature applications many benefits may be obtained by using ORC instead of steam rankine process [3].

Solar collectors and thermal energy storage components are the two core subsystems in solar thermal applications. A solar collector which is the special energy exchanger converts solar irradiation energy to the thermal energy of the working fluid in solar thermal applications. Solar collectors need to have good optical performance in order to absorb heat as much as possible. For solar thermal applications, solar irradiation is absorbed by a solar collector as heat and then is transferred to the working fluid. The heat carried by the working fluid can be used to either provide domestic hot water or to charge a thermal energy storage tank from which the heat can be drawn for use later [4]. The aim of this research is to develop a model for predicting the net power output of a solar organic rankine cycle.

2. THE SOLAR ORC SYSTEM CONFIGURATION

The solar evacuated tube collector is heated using the energy from the sun, the heat from the sun causes the fluid in the collector (heat transfer fluid) to gain an increase in temperature and it then flows to the evaporator/storage unit where there is heat exchange between the heat transfer fluid (water) and the working fluid (refrigerant).

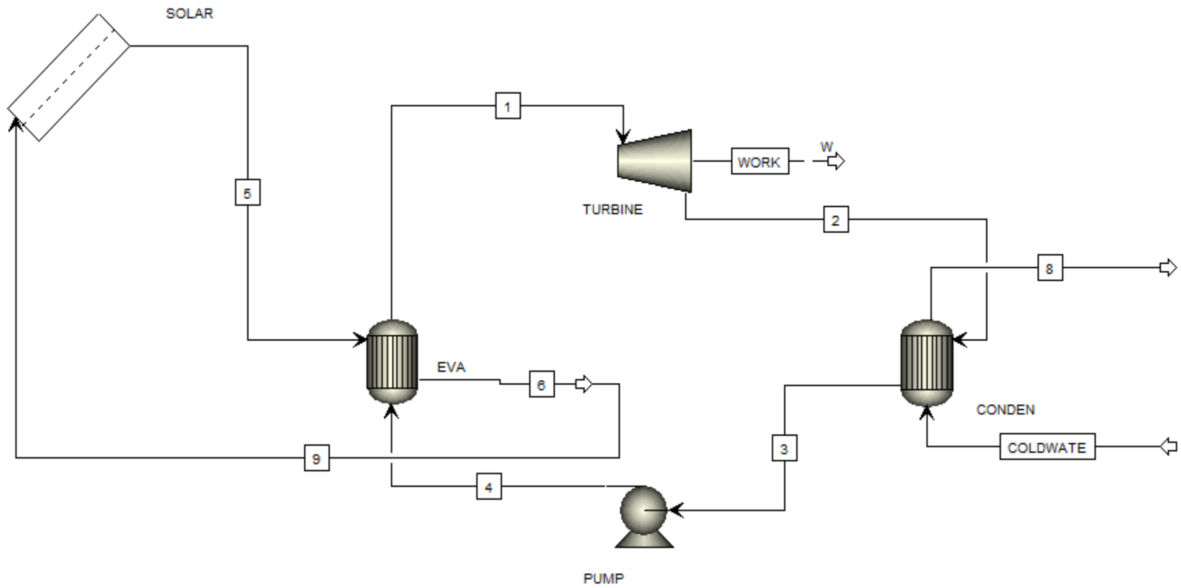

Figure 1. Schematic diagram of solar ORC.

As the working fluid gains more energy and increase in temperature, it moves to the expander/turbine where it causes expansion within the system and it connects to the generator for producing electricity. The remaining part of the refrigerant goes to the condenser where it loses energy in form of a drop in temperature as it mixes with cold water. The working fluid is then pumped back to the evaporator and the cycle continues.

3. THERMODYNAMIC ANALYSIS

Data were collected putting into mind the site and location which is been used as case study. 1kW was fixed at the turbine/expander output, thermodynamic assumptions were used to conduct the thermodynamic analysis of this research putting into consideration the boundary conditions and the operational parameters are shown in table 1.

The system was then simulated using MATLAB environment under steady state condition. The following equations were used for the analysis and also the parametric and sensitivity analysis.

i. **Evaporator model**

$$\boldsymbol{Q_e = m_f(h_1 - h_4) = m_f C_{p,wf}(T_{C.I} - T_{C.O})} \quad \textbf{(1)}$$

The total heat rate in the evaporator from the heat transfer fluid (HTF) into the working fluid is given by using equation 1.

$Q_e = Heat\ rate\ of\ the\ evaporator, m_f = massflow\ rate\ of\ the\ heat\ trasfer\ fluid,\ h_1 = Specific\ enthalpy\ at\ inlet,\ h_4 = Specific\ enthalpy\ at\ outlet,\ C_{p,wf} = Specific\ capacity\ of\ water, T_{C.I} = Temperature\ at\ inlet\ of\ the\ evaporator.$
$T_{C.O} = Temperature\ at\ outlet\ of\ the\ evaporator.$

ii. **Expander/turbine model**

$$\boldsymbol{W_t = m_f(h_1 - h_{2S})\eta_t \eta_g = m_f(h_1 - h_2)\,\eta_g} \quad \textbf{(2)}$$

The organic fluid which is the working fluid vapour passes through the expander/turbine to generate mechanical power. The turbine/expander can be analyzed using equation 2.

Where $\eta_t\ and\ \eta_g$ are the turbine/expander isentropic efficiencies and generator efficiency respectively. $h_1, h_{2S},\ h_2$ are the specific enthalpies of the working fluid at the expander inlet, expander outlet under ideal and actual conditions respectively.

iii. **Condenser model**

$$\boldsymbol{Q_C = m_f(h_2 - h_3) = m_f C_{p,w}(T_{C.O} - T_{C.I})} \quad \textbf{(3)}$$

The exhaust vapour at the expander exit is directed to the condenser where it is converted to the liquid state by rejecting its heat to the cooling water. This condenser heat rate can be estimated using equation 3.

$Where\ \boldsymbol{Q_C, m_f\ , h_2\ ,\ h_3}$ are the heat generated, mass flow rate of the working fluid, specific enthalpy at condenser inlet and outlet respectively $\boldsymbol{m_w\ , C_{p,w}\ , T_{C.O}}\ and\ \boldsymbol{T_{C.I}}$ are the cooling water mass flow rate, specific capacity of water, cooling water temperature of outlet and inlet of the condenser respectively.

iv. **Pump model**

$$\boldsymbol{W_p = \frac{m_f\, v_3\,(P_4 - P_3)}{\eta_p} = \frac{m_{f(h_{4S} - h_3)}}{\eta_p}} \quad \textbf{(4)}$$

The power consumed by the working fluid pump is estimated using equation 4. $Where\ \boldsymbol{W_p, m_f\ , v_3, P_4, P_3, h_4, h_3}\ and\ \boldsymbol{\eta_p}$ are pump work, working fluid mass flow rate, specific volume, pressure outlet, pressure inlet, specific enthalpy outlet, specific enthalpy inlet and pump efficiency of the pump respectively.

v. **Net power output and system efficiency**

The net power output generated by the SORC system is given as:

$$\boldsymbol{W_{net} = W_t - W_p} \quad \textbf{(5)}$$

The thermal efficiency of the ORC is the ratio of the net power output to the heat input in the evaporator. It can be expressed as:

$$\boldsymbol{\eta_{ORC} = \frac{W_{net}}{Q_e}} \quad \textbf{(6)}$$

The overall efficiency of the solar ORC system can be defined as follows:

$$\boldsymbol{\eta_{OVR}} = \frac{\boldsymbol{W_{net}}}{\boldsymbol{G_I \times A_{COL}}} \quad \textbf{(7)}$$

Table 1. Input parameters

S/N	Component	Level 1	Level 2	Level 3
1	Low/medium SORC area	$32m^2/16m^2$	$30m^2/15m^2$	$28m^2/14m^2$
2	Low/medium solar ORC temperature	$95\ ^OC/130\ ^OC$	$90\ ^OC/120\ ^OC$	$85\ ^OC/110\ ^OC$
3	Pinch temperature difference at evaporator	$10\ ^OC$	$10\ ^OC$	$10\ ^OC$
4	Low/medium ORC evaporator temperature	$85\ ^OC/\ 120\ ^OC$	$80\ ^OC/\ 110\ ^0C$	$75\ ^OC/\ 100\ ^OC$
5	Expander power output	1kW	1kW	1Kw
6	Condenser outlet temperature	$42\ ^0C$	$42\ ^0C$	$42\ ^0C$
7	Expander efficiency	70%	70%	70%
8	Pump efficiency	70%	70%	70%
9	Solar collector efficiency	70%	70%	70%
10	Generator efficiency	95%	95%	95%

4. RESULTS

Table 2, 3 and 4 shows the result gotten form the thermodynamic analysis of using the equations from section 3.0.

Table 2. Result for both R134a and R245fa for level 1

Parameters	R134a	R245fa
h_1	427.760 kJ/kg	484.390 kJ/kg
h_2	409.830 kJ/kg	435.160 kJ/kg
h_{2S}	402.130 kJ/kg	414.060 kJ/kg
h_3	259.410 kJ/kg	255.290 kJ/kg
h_4	261.040 kJ/kg	256.580 kJ/kg
h_{4S}	260.550 kJ/kg	256.190 kJ/kg
m_f	0.059 kg/s	0.021 kg/s
Q_E	9.782 kW	4.871 kW
Q_C	8.825 kW	3.846 kW
W_P	0.096 kW	0.028 kW
W_{net}	0.905 kW	0.973 kW
η_{ORC}	0.093	0.200
η_{SORC}	0.000028	0.000060

Table 3. Result for both R134a and R245fa for level 2

Parameters	R134a	R245fa
h_1	428.810 kJ/kg	479.740 kJ/kg
h_2	412.240 kJ/kg	435.160 kJ/kg
h_{2S}	405.140 kJ/kg	416.050 kJ/kg
h_3	259.410 kJ/kg	255.290 kJ/kg
h_4	260.780 kJ/kg	256.300 kJ/kg
h_{4S}	260.370 kJ/kg	255.990 kJ/kg
m_f	$0.064\ kg/s$	$0.024\ kg/s$
Q_E	$10.670\ kW$	$5.275\ kW$
Q_C	$9.710\ kW$	$4.247\ kW$
W_P	$0.087\ kW$	$0.024\ kW$
W_{net}	$0.913\ kW$	$0.976\ kW$
η_{ORC}	0.086	0.185
η_{SORC}	0.000030	0.000065

Table 4. Result for both R134a and R245fa for level 3

Parameters	R134a	R245fa
h_1	429.020 kJ/kg	474.260 kJ/kg
h_2	414.170 kJ/kg	435.160 kJ/kg
h_{2S}	407.810 kJ/kg	418.410 kJ/kg
h_3	259.410 kJ/kg	255.290 kJ/kg
h_4	260.550 kJ/kg	256.060 kJ/kg
h_{4S}	260.210 kJ/kg	255.830 kJ/kg
m_f	$0.071\ kg/s$	$0.027\ kg/s$
Q_E	$11.940\ kW$	$5.874\ kW$
Q_C	$10.970\ kW$	$4.842\ kW$
W_P	$0.081\ kW$	$0.021\ kW$
W_{net}	$0.919\ kW$	$0.979\ kW$
η_{ORC}	0.077	0.167
η_{SORC}	0.000032	0.000069

4.1. Parametric and Sensitivity Analysis

A parametric sensitivity analysis was carried out using the simulated result. Figure 2 to 11 shows the variation of the design parameters and the performance of the solar organic rankine cycle. It shows that mass flow rate, heat generated and area $(m_f, Q_g\ and\ A_{COL})$ are very important parameters for optimizing the performance of the solar organic rankine cycle.

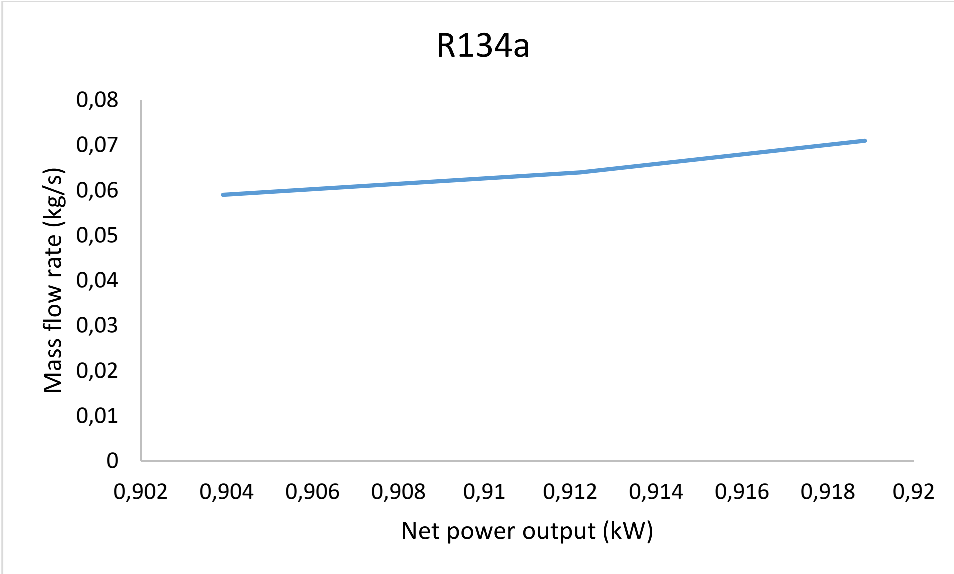

Figure 2. Mass flow rate against net power output

Figure 2 shows that the net power output increase significantly with the increase of the mass flow rate. The mass flow rate is a key parameter in enhancing the performance of the system. From various literature reviewed, the higher the mass flow rate the more expensive is the pump and as such an equilibrium has to be meet. So as not to increase the running cost of the overall system.

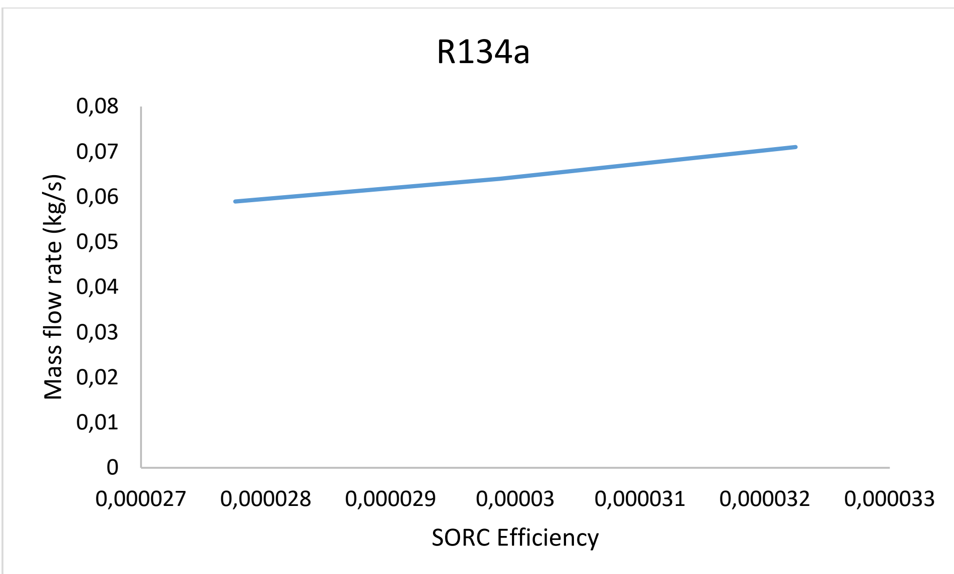

Figure 3. Mass rate flow against SORC efficiency

Figure 3 shows the effect of mass flow rate on the solar organic rankine cycle, an increase in the mass flow rate yields to an increase in the solar organic rankine cycle efficiency.

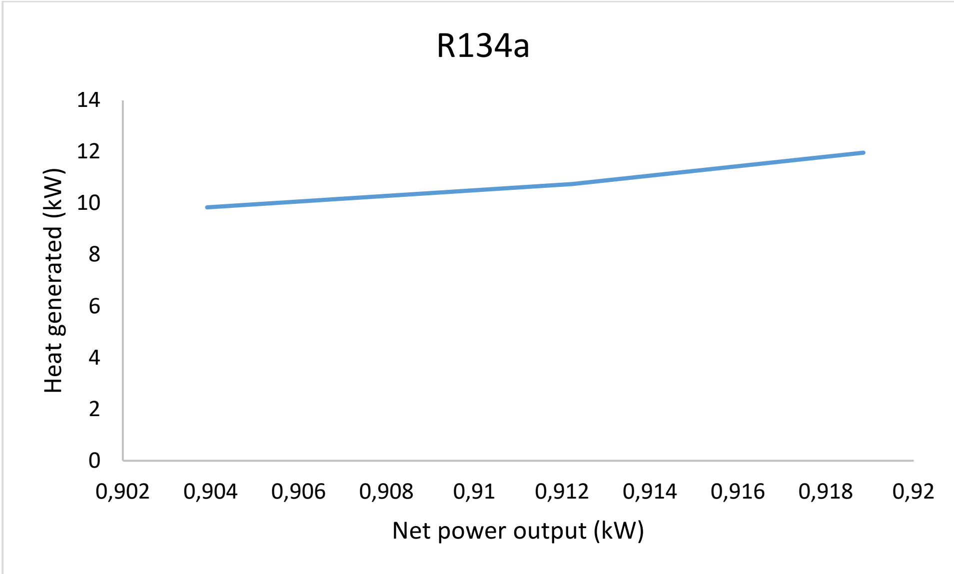

Figure 4. Heat generated against net power output

An increase in the heat generated leads to an increase in the net power output as shown in figure 4. This is as a result of the temperature of the working fluid at the evaporator exit into the turbine/expander.

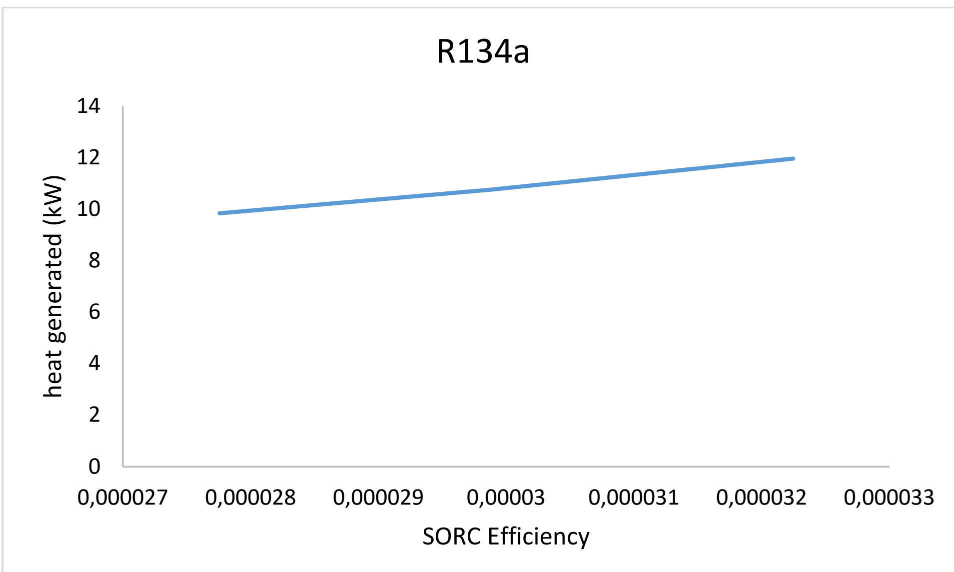

Figure 5. Heat generated against SORC efficiency

The heat generated affects the solar organic rankine cycle directly as shown in figure 5, an increase in heat generated results to a significant increase in the overall solar organic rankine efficiency of the plant. The mass flow rate and the enthalpy change of the evaporator yields the heat generated and as such the mass flow rate, enthalpy of entering and exit of the evaporator are optimal parameters to be considered.

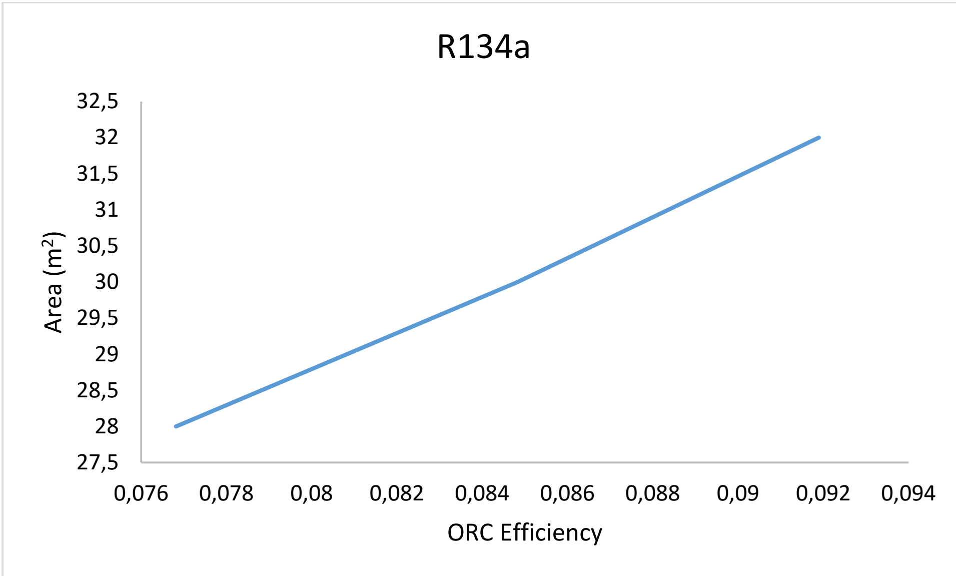

Figure 6. Area against ORC efficiency

Figure 6 shows that the area of the collector has great effect on the organic rankine cycle. This infers that an increase in the area of the collector results to a large increase of the organic rankine cycle efficiency. The larger the area the more expensive is the cost of the overall plant and as such the size of the solar collector is a very important factor to consider during the design of a solar power plant.

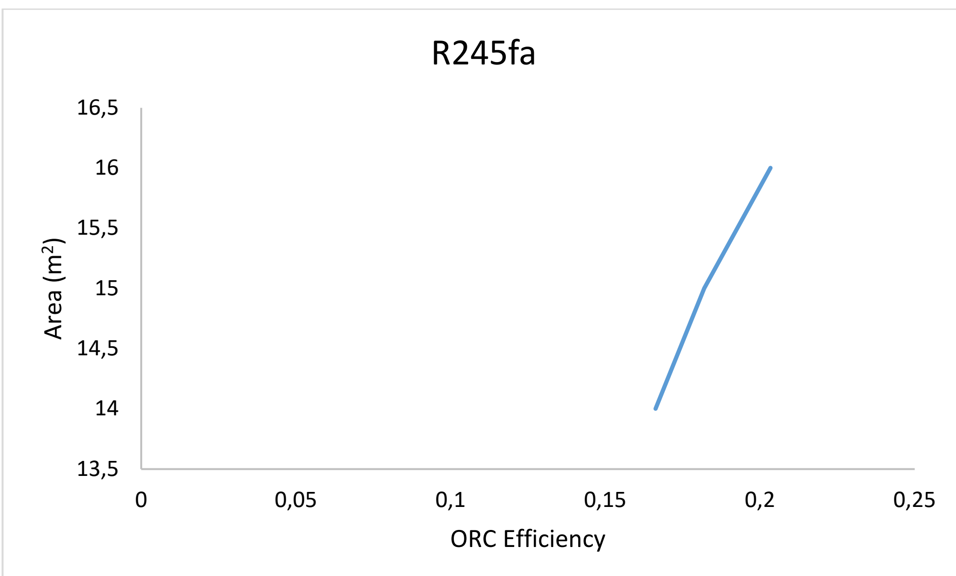

Figure 7. Area against ORC efficiency

As shown in figure 7, the refrigerant considered is R245fa and it shows that the area has a direct effect on the organic rankine cycle. An increase in the area leads to an increase in the organic rankine cycle efficiency.

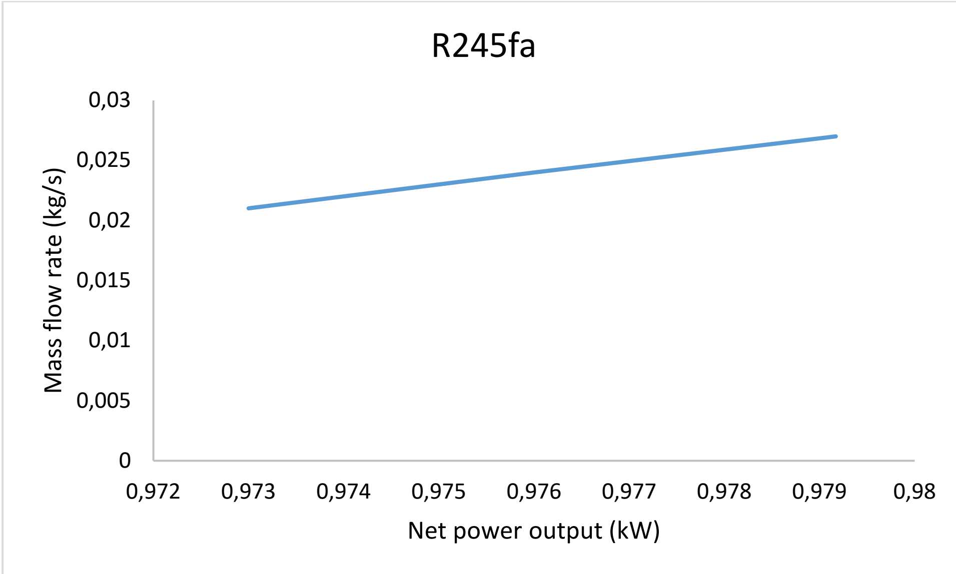

Figure 8. Mass flow rate against net power output

Figure 8 shows the direct relationship between mass flow rate and net power output using R245fa. An increase in the mass flow rate causes a significant increase in the net power output, this means that the higher the mass flow rate the higher the power produced by the turbine.

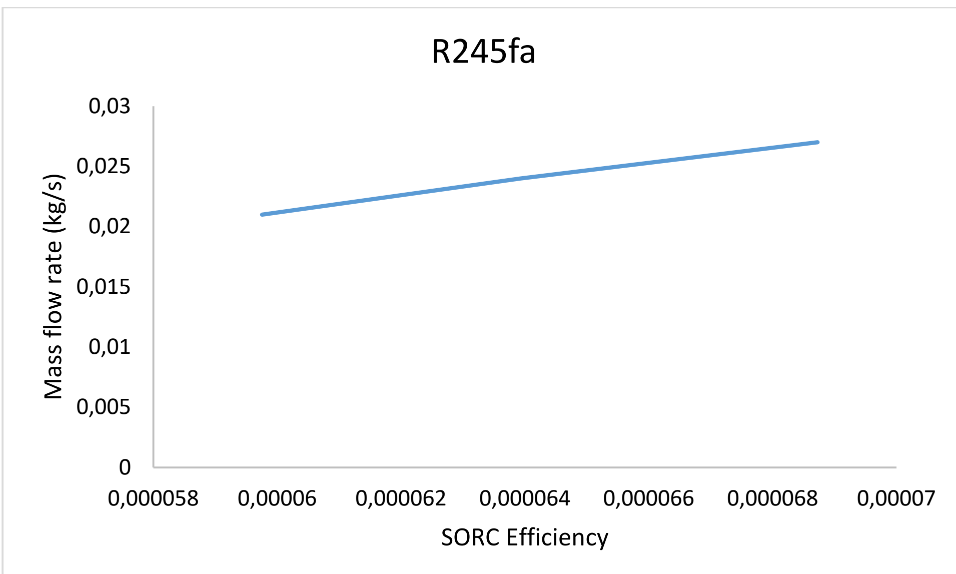

Figure 9. Mass flow rate against SORC efficiency

The mass flow rate affects the overall solar organic rankine cycle as shown in figure 9. An increase in the mass flow rate leads to an increase in the overall solar efficiency of the power plant.

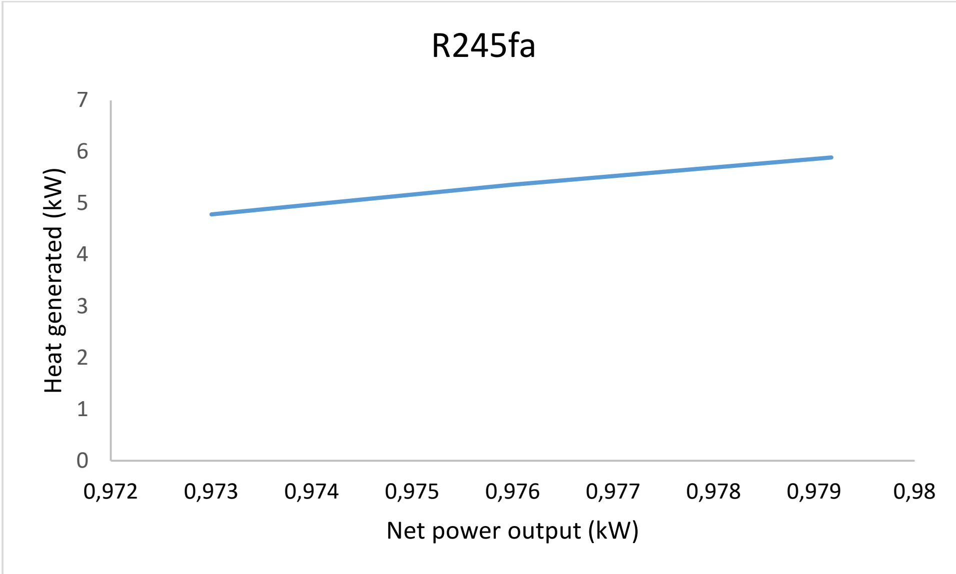

Figure 10. Heat generated against net power output

Figure 10 shows that the higher the heat generated the higher the net power output, the heat generated is one of the important parameters to consider for optimal condition of the solar organic rankine cycle.

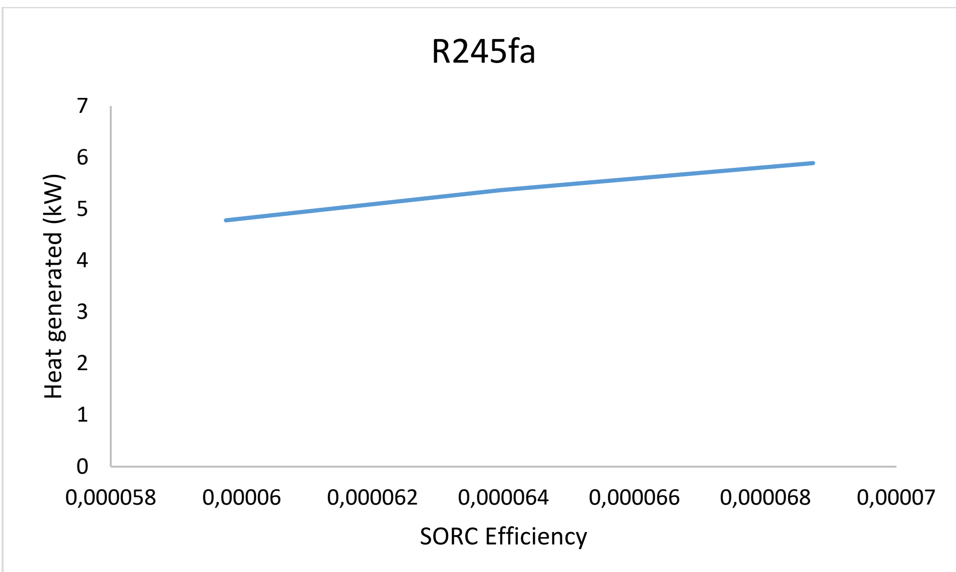

Figure 11. Heat generated against SORC efficiency

Considering R245fa as shown in figure 11, it shows the direct relationship between the heat generated by the evaporator and the overall solar organic rankine cycle efficiency. The higher the heat generated the higher the overall solar organic rankine cycle efficiency.

5. CONCLUSION

The various levels show the different conditions the SORC can be subjected to. The heat generated by the evaporator, organic rankine cycle efficiency and the overall solar organic rankine cycle efficiency are 9.782kW and 4.871kW, 9.3% and 20%, 0.0028% and 0.006% respectively. This shows that the temperature of R245fa at 120 ^{O}C generates a higher organic rankine cycle efficiency and overall cycle efficiency. R134fa generates a higher heat energy at the evaporator, the efficiencies are low due to its limitation of its critical temperature of 101.06 ^{O}C.

Table 3 shows how the system performed when the temperature entering the turbine using both refrigerant (R134a and R245fa) at 80 ^{O}C and 110 ^{O}C. The heat generated, organic rankine cycle efficiency and overall solar organic rankine cycle efficiency are 10.670kW and 5.275kW, 0.086 and 0.185, 0.000030 and 0.000065 respectively. Comparing result from both table 4.2 and table 4.1, it shows that the heat generated as shown in table 4.2 is higher than that in table 4.1, the organic rankine cycle efficiency is lower in table 4.2 and an increase in the overall solar organic rankine cycle efficiency. The organic rankine cycle efficiency is lower as a result of the decrease in the turbine intake temperature and a reduction in the area of the solar collector causes a reduction in the solar organic rankine cycle efficiency.

Table 4 gives a higher heat generated, a lower organic rankine cycle efficiency and a higher overall solar organic rankine cycle efficiency. A reduction in the temperature of the working fluid entering the turbine result in a decrease of the organic rankine cycle efficiency and a reduction in the solar collector area give rise to a decrease in the organic rankine cycle efficiency.

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