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EFFECT OF REGENERATIVE ORGANIC RANKINE CYCLE (RORC) ON THE PERFORMANCE OF SOLAR THERMAL POWER IN YOGYAKARTA, INDONESIA

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Abstract

This paper presents effect of Regenerative Organic Rankine Cycle (RORC) on the performance of solar thermal power in Yogyakarta, Indonesia. Solar thermal power is a plant that uses solar energy as heat source. Indonesia has high humidity level, so that parabolic trough is the most suitable type of solar thermal power technology to be developed, where the design is made with small focal distance. Organic Rankine Cycle (ORC) is a Rankine cycle that use organic fluid as working fluid to utilize low temperature heat sources. RORC is used to increase ORC performance. The analysis was done by comparing ORC system with and without regenerator addition. Refrigerant that be used in the analysis is R123. Preliminary data was taken from the solar collector system that has been installed in Yogyakarta. The analysis shows that with 36 m total parabolic length, the resulting solar collector capacity is 63 kW, heat input/evaporator capacity is determined 26.78 kW and turbine power is 3.11 kW for ORC, and 3.38 kW for RORC. ORC thermal efficiency is 11.28% and RORC is 12.26%. Overall electricity efficiency is 4.93% for ORC, and 5.36% for RORC. With 40°C condensing temperature and evaporation at 10 bar saturated condition, efficiency of RORC is higher than ORC. Greater evaporation temperature at the same pressure (10 bar) provide greater turbine power and efficiency.

Keywords: solar thermal power, parabolic trough, regenerative organic Rankine cycle, regenerator, R123.

I. INTRODUCTION

Nowadays renewable energy development is very important to overcome energy problem in the world. Solar energy is a potential renewable energy source for solving energy problems. Indonesia is a tropical country which has good solar radiation (4.8 $kWh/m^2/day$) [1], so it is good for developing solar energy. Concentrating solar energy is a very promising technology among solar energy conversion systems, and parabolic troughs are the most mature application solar thermal technologies in the market [2]. Parabolic trough technology was chosen to be developed by LIPI, because Indonesia has high humidity, so it was designed with small focal distance [3, 4]. LIPI is developing parabolic trough by using Organic Rankine Cycle (ORC) for electricity generation system, because it has low temperature heat sources.

ORC is a Rankine cycle that use organic fluid as working fluid to utilize low temperature heat sources. ORC is one of the best used and promising ways in low heat source applications than many well-proven technologies [5]. ORC system ensures high efficiencies for small-scale applications and/or low temperature heat sources, compared with other alternative technologies [6-10]. Furthermore, ORC shows high flexibility, safety and low costs and maintenance requirements [11-14]. Quoilin *et al*. presented the design of a solar organic Rankine cycle installed in Lesotho, where the system consisted of parabolic trough collectors, a thermal storage tank, and a small-scale ORC system using scroll expanders. The results show that the overall electricity efficiency of the system could reach 7% and 8% [15].

The selection of the working fluid in the ORC system is very important to produce optimal performance. Dry and isentropic fluids are the most preferred working fluid for the ORC [16]. The research in this paper is using R123 as organic fluid. R123 was able to improve the ORC performance significantly for low grade heat

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source application [17]. Overall efficiency for ORC cycle using R123 as working fluid and coupled to CPC collectors was about 7.9% for a solar intensity of 800 W/m^2 and an evaporating temperature of 147°C [5]. R123 was a better working fluid than R12 and R134a for a waste heat recovery on the work output and efficiency of thermodynamic first law and second law system [18, 19].

Performance of ORC can be improved by regenerative organic Rankine cycle (RORC). Regenerator is used as an addition component for RORC. Regenerator addition can improve system efficiency [20, 21]. Regenerator is also used when the fluid is still strongly overheated after the expansion in the turbine. Regenerator is located at the exhaust of turbine on the low pressure side, and between the pump and evaporator on the high pressure side. This reduces the heat duty of the condenser and at the same time raises the enthalpy of the working fluid leaving the pump. This condition can improve thermodynamic efficiency [22].

Compared with ORC, RORC with a lower irreversibility produces higher efficiency while also reducing the amount of waste heat required to produce the same power [23]. Xu Rong Ji *et al.* [24] proposed RORC that used a vapor injector as regenerator, where the results showed that there existed the inlet vapor pressure regions for the injector that allowed the new cycle performed better than the basic ORC. Pei Gang *et al.* [25] analyze that the system electricity efficiency with RORC for irradiance 750 W/m^2 is about 8.6% and is relatively higher than ORC by 4.9%. This paper presents effect of Regenerative Organic Rankine Cycle (RORC) on the performance of solar thermal power by using R123 as organic fluid. Analysis was done by using data from solar collector that has been built in Yogyakarta by varying evaporating temperature.

II. System Description and Working Principle

Solar collector unit in the form of parabolic trough serves to capture solar heat energy. The heat is stored in thermal storage tank. Through heat transfer fluid circulation with 200°C maximum temperature, the heat energy is used to vaporize organic fluid in the evaporator at ORC system as organic turbine driver. Rotary of turbine shaft is then connected to generator to produce electricity. This system can be operated in hybrid with other heat sources such as biomass. In this research, the heat transfer fluid is palm oil and organic fluid is R123. Basic ORC consists of evaporator, turbine, condenser and feeder pump. Evaporator is a component for heating working fluid from liquid to vapor to be expanded in turbine. Turbine is a component for expanding vapor to produce electricity by generator. Condenser is a component for condensing vapor from the turbine, and feeder pump is a component for pumping fluid from low pressure to high pressure.

Regenerative Organic Rankine Cycle (RORC) is made to utilize the heat of the working fluid at the superheated condition after undergoing expansion in the turbine. Regenerator is added to make use of a working fluid that is in the form of vapor from turbines, so the heat can be used to increase working fluid enthalpy leaving the pump. The addition of regenerator would increase the efficiency of the system as waste heat in the regenerator after expanded utilized to heat the fluid when it will go into the evaporator, so that the waste heat will be reduced. Schematic of RORC is showed in Figure 1.

Parabolic trough has been built in UPT BPPTK Yogyakarta. The design was made with 6 modules where specification of each module is 3.5 m of aperture width and 6 m of parabolic length. This means for 6 modules, total parabolic

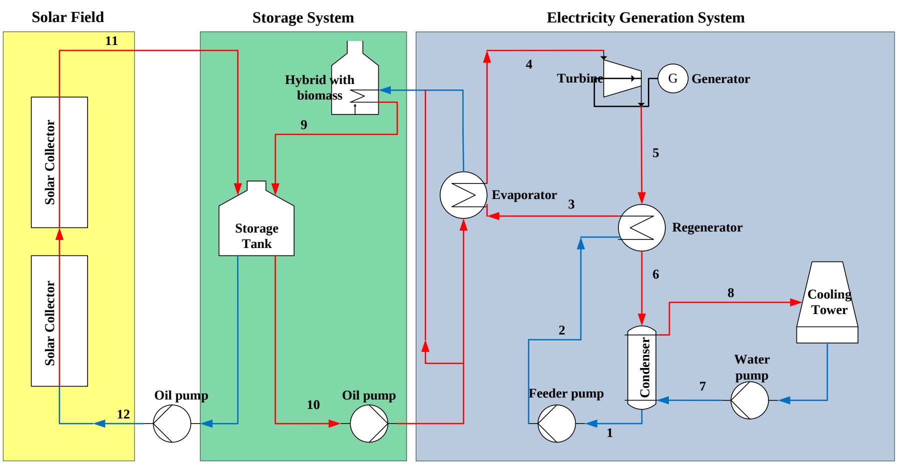

Figure 1. Schematic of Regenerative Organic Rankine Cycle (RORC)

Figure 2. Parabolic trough solar collector (PTSC)

length is 36 m. PTSC design was made as preliminary data for determining ORC and RORC as electricity generation system. Figure 2 shows parabolic trough solar collector that has been built in UPT BPPTK Yogyakarta. Working fluid which is used in the system is R123. R123 is a low pressure refrigerant, so it is good for low working pressure system. Table 1 [26] shows physical and thermodynamic properties of R123.

Table 1.
Physical and thermodynamic properties of R123

Characteristics	Properties
Chemical name	2,2-dichloro-1,1,1-trifluoroethane
Chemical formula	$CHCl_2CF_3$
Slope of saturation vapor line	Isentropic
Molecular weight	152.9 g/mol
Boiling temperature	27.8°C
Critical temperature and pressure	183.7°C, 36.68 bar
ODP[a]	0.02
GWP[b]	77
Hazard rating[c]:	
Health	2
Flammability	1
Reactivity	0

[a] Relative to R11; [b] Relative to CO_2 (100 y time horizon); [c] Hazard rating: 0 = no hazard, 1 = slightly hazardous, 2 = moderately hazardous, 3 = severely hazardous, 4 = extremely hazardous

III. Basic Calculation

Calculation of solar thermal power using the RORC is divided into two parts. First part is in solar field and storage system area, and the second is at electricity generation system (RORC). Flow diagram for determining performance of the solar thermal power optimization using RORC is showed in Figure 3.

Preliminary data of solar collector that has been built in Yogyakarta is used for determining performance of solar collector using RORC. Aperture width and parabolic length as basic data are used to calculate aperture area using equation

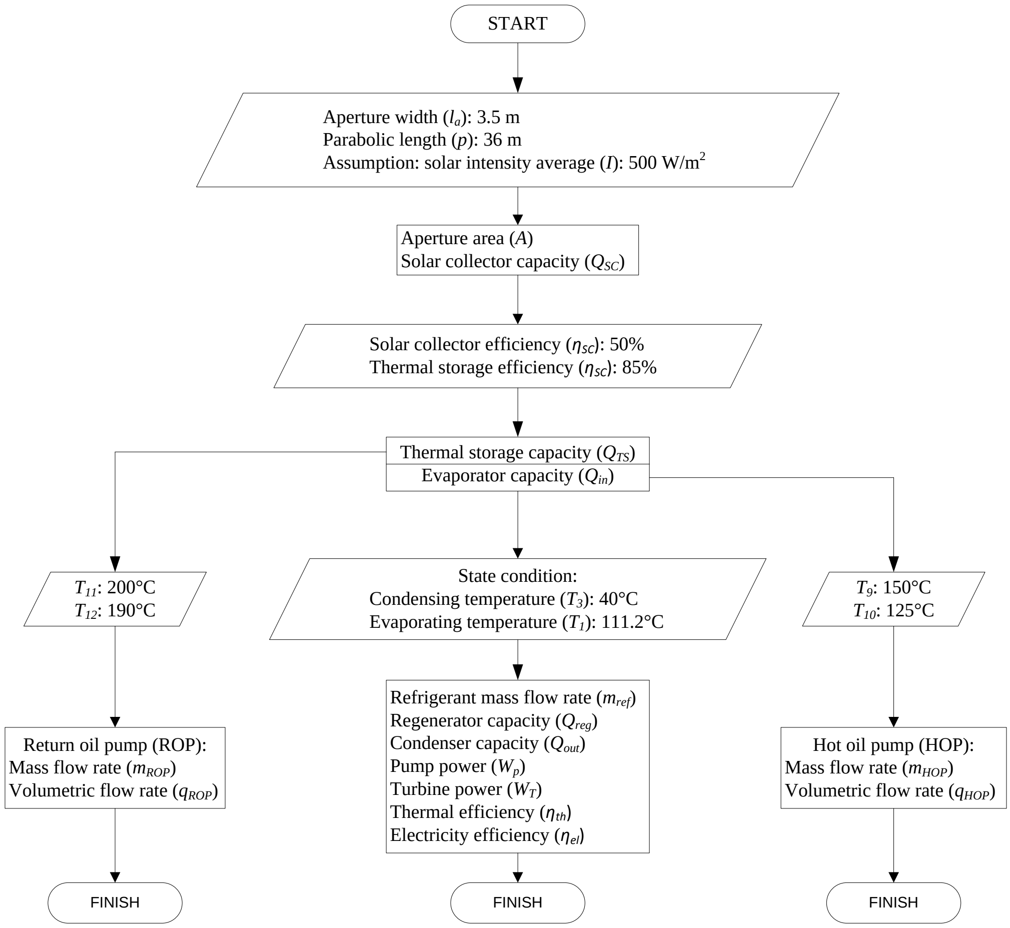

Figure 3. Flow diagram design optimization of solar thermal power using RORC

(1). By an assumption average solar intensity, solar collector capacity is determined by equation (2).

$$A = p \times l_a \quad (1)$$

$$Q_{SC} = I \times A \quad (2)$$

Where
A : aperture area (m^2)
p : parabolic length (m)
l_a : aperture width (m)
Q_{SC} : solar collector capacity (kW)
I : solar intensity (W/m^2)

By solar collector efficiency of 50% [27], thermal storage capacity is determined by equation (3). Heat input/evaporator capacity is determined to be preliminary data for RORC calculation. With an assumption of 85% thermal storage capacity, heat input/evaporator capacity is showed by equation (4).

$$Q_{TS} = Q_{SC} \times \eta_{SC} \quad (3)$$

$$Q_{in} = Q_{TS} \times \eta_{TS} \quad (4)$$

Where
Q_{TS} : thermal storage capacity (kW)
η_{SC} : solar collector efficiency
Q_{in} : heat input/evaporator capacity (kW)
η_{TS} : thermal storage efficiency

Mass flow rate of return oil pump and hot oil pump are determined to calculate volumetric flow rate. It is used to select pump to be used for the system. Mass flow rate and volumetric flow rate calculation are showed by equation (5) and (6) [28].

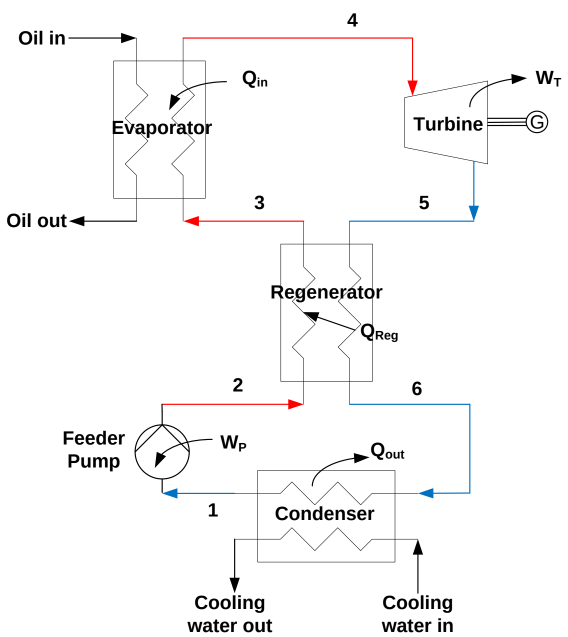

Figure 4. Regenerative organic Rankine cycle (RORC)

$$\dot{m}_{OP} = \frac{Q_{TS}}{Cp_{OP} \times (T_{in} - T_{out})} \quad (5)$$

$$q_{OP} = \frac{\dot{m}_{OP}}{\rho_{OP}} \quad (6)$$

Where
$\dot{m}_{OP}$: mass flow rate of return/hot oil pump (kg/s)
Cp_{OP} : specific heat fluid at average temperature (kJ/kg °C)
T_{in} : inlet temperature (°C)
T_{out} : outlet temperature (°C)
q_{OP} : volumetric flow rate of return/hot oil pump (m^3/s)
ρ_{OP} : density of palm oil at average temperature (kg/m^3)

IV. THERMODYNAMIC ANALYSIS

Regenerative Organic Rankine Cycle (RORC) is analyzed to increase solar thermal power performance that has been built in Yogyakarta. Heat input/evaporator capacity is a preliminary data to determine the performance. With regenerator addition, RORC is showed by Figure 4. Each of RORC components can be determined. Red lines show high pressure and blue lines show low pressure. Thermodynamic analysis is used as standard calculation to determine performance of RORC. T-s diagram is made to simplify the calculation. T-s diagram of R123 is showed in Figure 5. Ideal (reversible) cycle at Figure 5 is showed in green colors, real (irreversible) cycle is showed in red colors, and regenerator addition at the cycle is showed in the other color with varying evaporation temperatures. The assumptions for analyzing RORC are steady state condition, working pressure through condenser and evaporator are constant, inlet pump fluid is saturated liquid, inlet condenser fluid is saturated vapor, turbine and pump work adiabatically, and kinetic and potential energy are negligible.

Thermodynamic analysis is started from feeder pump and turbine efficiency. Equation (7) and (8) are used to determine enthalpy at outlet

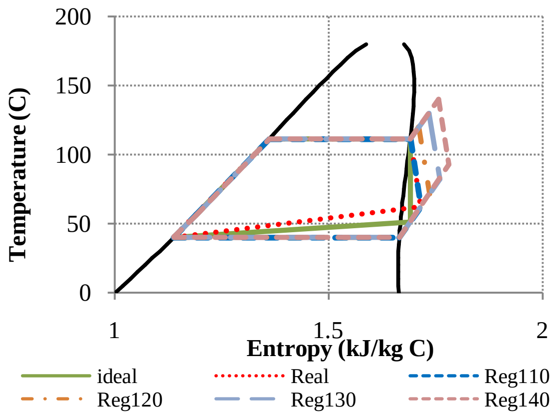

Figure 5. T-s diagram of R123

pump/inlet regenerator (h_2) and enthalpy at outlet turbine/inlet regenerator (h_5).

$$\eta_p = \frac{h_{2s} - h_1}{h_2 - h_1} \tag{7}$$

$$\eta_T = \frac{h_4 - h_5}{h_4 - h_{5s}} \tag{8}$$

Where

η_p : pump isentropic efficiency
η_T : turbine isentropic efficiency
h_1 : enthalpy at inlet pump/outlet condenser (kJ/kg)
h_2 : enthalpy at outlet pump/inlet regenerator (kJ/kg)
h_{2s} : enthalpy isentropic at outlet pump/inlet regenerator (kJ/kg)
h_4 : enthalpy at inlet turbine/outlet evaporator (kJ/kg)
h_5 : enthalpy at outlet turbine/inlet regenerator (kJ/kg)
h_{5s} : enthalpy isentropic at outlet turbine/inlet regenerator (kJ/kg).

Next step is calculating enthalpy at output regenerator/input evaporator (h_3) and refrigerant mass flow rate ($\dot{m}_{ref}$). Balance energy in regenerator at equation (10) is used to calculate h_3, and balance energy in evaporator at equation (11) is used to calculate $\dot{m}_{ref}$. After calculating h_3 and $\dot{m}_{ref}$, then regenerator capacity (Q_{reg}) at equation (9) can be determined.

$$Q_{reg} = \dot{m}_{ref}\, h_5 - \dot{m}_{ref}\, h_6 = \dot{m}_{ref}\, h_3 - \dot{m}_{ref}\, h_2 \tag{9}$$

$$h_3 = h_5 + h_2 - h_6 \tag{10}$$

$$\dot{m}_{ref}\, h_3 + Q_{in} = \dot{m}_{ref}\, h_4 \tag{11}$$

Where

Q_{reg} : regenerator capacity (kW)
h_3 : enthalpy at output regenerator/input evaporator (kJ/kg)
h_6 : enthalpy at outlet regenerator/inlet condenser (kJ/kg)
$\dot{m}_{ref}$: mass flow rate of refrigerant (kg/s)
Q_{in} : heat input/evaporator capacity (kW).

Balance energy of condenser, feeder pump and turbine are showed by equation (12), (13) and (14).

$$\dot{m}_{ref}\, h_6 = \dot{m}_{ref}\, h_1 + Q_{out} \tag{12}$$

$$\dot{m}_{ref}\, h_1 + W_P = \dot{m}_{ref}\, h_2 \tag{13}$$

$$\dot{m}_{ref}\, h_4 = \dot{m}_{ref}\, h_5 + W_T \tag{14}$$

Where

Q_{out} : heat output/condenser capacity (kW)
W_P : pump power (kW)
W_T : turbine power (kW)

After calculating capacity and power of each component, thermal efficiency of RORC and electricity efficiency can be determined. Thermal efficiency and electricity efficiency are showed by equation (15) and (16).

$$\eta_{th} = \frac{W_T - W_p}{Q_{in}} \tag{15}$$

$$\eta_{el} = \frac{W_T}{Q_{SC}} \tag{16}$$

Where

η_{th} : thermal efficiency of RORC
η_{el} : electricity efficiency of RORC

V. RESULTS AND DISCUSSION

RORC is analyzed to determine its effect to solar thermal power that has been built in Yogyakarta. Result of RORC for basic calculation is showed by Table 2. Result for basic calculation shows that for 36 m parabolic length and average solar intensity 500 W/m^2, solar collector capacity is 63 kW and the heat input (evaporator capacity) is 26.78 kW. The heat input is then used as a data to determine performance of RORC as electricity generation system. Another data for RORC to determine properties of each point are low pressures at 1.545 bar (40°C) and high pressures at 10 bar (111.2°C). Result for RORC is showed by Table 3. The result shows that turbine power increase from 3.11 kW to 3.38 kW by using RORC. Thermal efficiency of the system also increases from 11.28% to 12.26%, and the overall electricity efficiency of the system increases from 4.93% to 5.36%. This means that regenerator addition can improve solar thermal power performance. If the experiments are arranged to higher evaporating temperature (until 140^{o}C), then result of the design with the same high pressure are showed in Figure 6 to Figure 12.

Figure 6 shows that regenerator capacity rises at the increasing evaporating temperature. This occurs because the superheat conditions cause more waste heat in the condenser, that waste heat is utilized in the regenerator to heat the working

Table 2.
Design result for basic calculation

Design result	Value
Aperture area (A)	126 m^2
Solar collector capacity (Q_{SC})	63 kW
Thermal storage capacity (Q_{TS})	31.5 kW
Evaporator capacity/heat input (Q_{in})	26.78 kW
Return oil pump mass flowrate ($\dot{m}_{ROP}$)	1.304 kg/s
Return oil pump volumetric flowrate (q_{ROP})	0.002 m^3/s
Hot oil pump mass flowrate ($\dot{m}_{HOP}$)	1.412 kg/s
Hot oil pump volumetric flowrate (q_{HOP})	0.002 m^3/s

Table 3.
Design result for electricity generation system

Design result	Ideal ORC	Real ORC	RORC
Refrigerant mass flowrate ($\dot{m}_{ref}$)	0.1310 kg/s	0.1312 kg/s	0.1425 kg/s
Refrigerant volumetric flowrate (q_{ref})	331.092 LPH	331.362 LPH	359.926 LPH
Turbine power (W_T)	4.14 kW	3.11 kW	3.38 kW
Condenser capacity/heat output (Q_{out})	22.69 kW	23.75 kW	23.49 kW
Regenerator capacity (Q_{reg})	-	-	2.31 kW
Thermal efficiency (η_{th})	15.22%	11.28%	12.26%
Overall electricity efficiency of the system (η_{el})	6.57%	4.93%	5.36%

fluid, so it can improve thermal efficiency of the system.

Figure 7 shows the rising of enthalpy entering evaporator at the increasing evaporating temperature in the RORC system. This occurs because at the higher evaporating temperature, there is more waste heat that can be used, thereby it can increase the enthalpy entering evaporator. On the other side, the enthalpy value of ideal and real ORC condition are both lower than the RORC system, because under these conditions there are no regenerator, so there are no heat to be utilized.

Figure 8 shows that the refrigerant mass flow rate in the RORC larger than the ideal and real ORC conditions. This is due to the increase in enthalpy entering evaporator, so that the difference in enthalpy at the evaporator inlet and outlet is smaller and cause the value of refrigerant mass flow rate increases. The refrigerant mass flow rate of ideal and real ORC condition are smaller than the RORC system, because there is no waste heat utilization in the system.

Heat output at RORC has a lower value with the increase of evaporation temperature (Figure 9). This occurs because the heat rejection in the condenser is utilized in the regenerator to support the increasing of enthalpy (Figure 7) when the working fluid is pumped to the evaporator. Therefore, the waste heat/heat rejection (which is cooled in the condenser) become smaller due to the heat recovery by the regenerator when vapor exit the turbine. Heat output at ideal ORC conditions is the smallest but its value is tend to increase, because greater evaporation temperature result greater waste heat. However, because the system is conditioned ideal ORC, the generated waste heat is smaller than real ORC condition. In real ORC condition, the value of heat output is the highest because the system is conditioned on the real ORC condition which there is no waste heat utilization (without regenerators).

Figure 10 shows that the turbine power on RORC system is rising in the greater evaporation temperature. This occurs due to the regenerator addition increases refrigerant mass flow rate (Figure 8), thus it increases the turbine power.

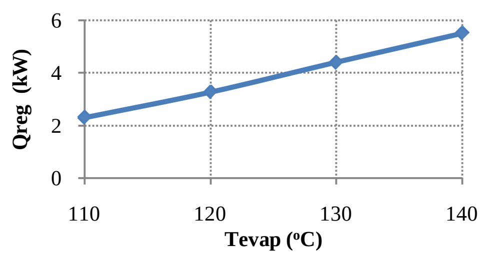

Figure 6. Regenerator capacity at varying evaporating temperature

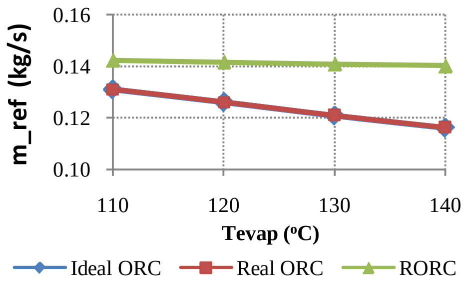

Figure 8. Refrigerant mass flowrate at varying evaporating temperature

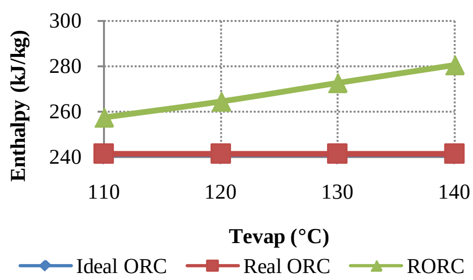

Figure 7. Enthalpy entering evaporator at varying evaporating temperature

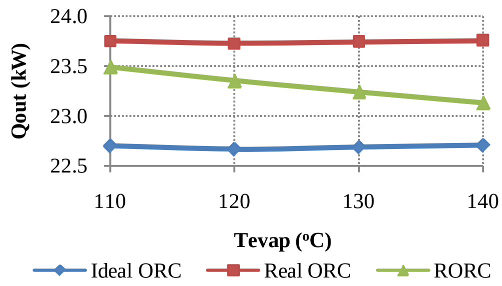

Figure 9. Heat output at varying evaporating temperature

Turbine powers in the ideal and real ORC condition tend to be smaller with the increasing of evaporation temperature. This happens because the superheat condition causes smaller turbine power and there is no waste heat recovery at the system.

Figure 11 shows that the RORC increases thermal efficiency by increasing evaporation temperature. This occurs due to the regenerator addition improves thermal efficiency of the system. Greater waste heat that can be used result greater thermal efficiency. Therefore, Figure 11 shows that greater evaporation temperature (superheated conditions) will increase thermal efficiency. Thermal efficiency of ideal and real ORC system are smaller by increasing evaporation temperature. This occurs because the superheated conditions will reduce performance of the system. Figure 12 shows the electricity efficiency of solar thermal power using RORC increases with the increasing of evaporation temperature. This occurs because the turbine power is increased, so that the generated electricity is greater. Conversely, ideal and real ORC generate smaller electricity with the increasing of evaporation temperature. This happens because smaller turbine power causes smaller electricity generation.

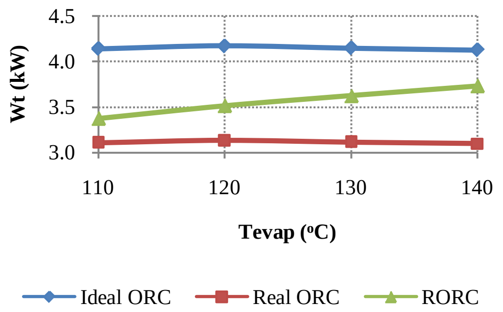

Figure 10. Turbine power at varying evaporating temperature

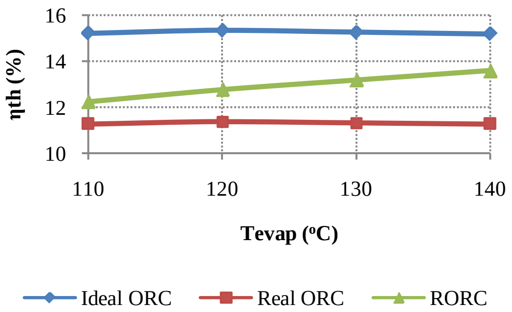

Figure 11. Thermal efficiency at varying evaporating temperature

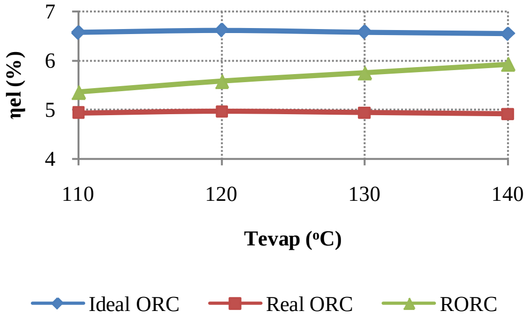

Figure 12. Electricity efficiency at varying evaporating temperature

VI. CONCLUSION

Effect of Regenerative Organic Rankine Cycle (RORC) on the performance of solar thermal power lead to the conclusion that with 63 kW solar collector capacities, the turbine power that be generated at the ideal ORC system is 4.14 kW, 3.11 kW for real ORC and 3.38 kW with the addition of regenerator (RORC). Thermal efficiency of the ideal ORC is 15.22%, 11.28% for real ORC and 12.26% for RORC. The results show that the RORC improve and enhance the performance of the system compare to the real ORC. The addition of regenerator is used to utilize waste heat from the turbine to the condenser, so the heat output is reduced/smaller and enthalpy entering evaporator become higher. These conditions will increase the turbine power, thermal and electricity efficiency of the system.

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