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PERFORMANCE STUDY OF SOLAR THERMAL BINARY POWER CYCLES

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ABSTRACT

The purpose of this study is to evaluate the performance of solar thermal binary power generating system. The system will consist of two cycles, which is solar superheated steam cycle and the organic Rankine cycle. Three organic fluids, isobutane, R123 and R245fa will be used in the study and will be compared with R134a. The primary heat energy is captured from solar energy is used for superheated steam power cycle. The rejected heat from condenser of the steam cycle is used as heat input for the organic Rankine cycle. The temperature differences in the condenser of steam cycle and evaporator of the organic Rankine cycle range from 10°C to 15°C. The total work is produced by the two turbines from these two cycles. The performance is measured based on work and efficiency of the cycles. For organic Rankine cycle, it is found that refrigerant R123 gives the highest efficiency among refrigerant R245fa, R134a and isobutane. It was found that, the maximum work from the combination of the two cycles is from solar steam/isobutane which can produce 613.22 kJ/kg work. This combination of solar Rankine cycle and organic Rankine cycle produce 542.4 kJ/kg and 70.82 kJ/kg maximum works respectively. Both of these solar superheated Rankine cycle and organic Rankine cycle achieve 19.76 % and 16.87 % efficiency respectively.

Keywords: *Binary power cycles, solar thermal, organic rankine cycles, parametric study, cycle efficiency.*

1.0 INTRODUCTION

Solar thermal is another alternative to extract energy from the sun. The solar radiation is used as a source to supply heat in order to produce power. Solar thermal is different from solar photovoltaic. Instead of using photoelectric effect, solar thermal uses the heat produced by solar energy. Usually solar thermal system is integrated with another cycle to produce power such as organic Rankine cycle. The heat gain from the sun is used to heat up working fluid in order to complete the cycle. This type of energy is good to the countries that receive solar radiation throughout a year.

The organic Rankine cycle system is more suitable for low temperature application. Organic Rankine cycle consists of condenser, evaporator, expansion device and valve. Sometimes the heat storage or backup boiler are installed together to solve the

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*Corresponding author : farid@fkm.utm.my problem during the monsoon season. When there is not enough solar radiation, the heat needed to operate the cycle is not enough. Therefore the backup boiler or heat storage is ideal to solve this problem.

Solar thermal is already applied for more than 50 years. There are lots of researches and development that have been done to improve the system. The system nowadays, uses the advantage of concentrating solar panel to extract heat from solar energy. Concentrating solar panel can provide double power generation compared with conventional solar panel. As the result, the number of solar collector panel can be reduced to almost half.

There are various types of design of solar collector that can be found nowadays. Solar collectors such as parabolic trough, central receiver and parabolic dish are examples on design of solar collector that available and used in power plant, (Lee, 2006). The variations of the design help the engineer to select type of solar collector suitable for the condition and environment of the power plant. Parabolic trough solar collector is the most interesting and lowest cost large-scale solar power technology available today. This is proven by 9 solar power plants developed by Luz International Limited. The solar field outlet temperature ranges from 306°C to 439°C can produce power 30,100 MWh to 256,125 MWh annually, (Price et. Al., 2002). Chena Hot Springs Resort demonstrated their moderate temperature geothermal organic Rankine cycle in July 2006 using Carrier refrigeration system, (Holdmann, 2007; Chena Power, 2010).

1.1 Organic Rankine Cycle

The evaluation of performance of organic Rankine cycle is done by making comparison of three different working fluids. Optimal system can be identified by varying different type of working fluids. The inlet temperature for turbine is determined to ensure the expansion process occur outside the mixture phase. The optimal point for turbine inlet temperature is at a point on saturated vapor line where the slope changes from negative slope to positive slope. The inlet turbine temperature is set on the saturated vapor line, (Cheng et. Al., 2005; Delgado-Torres et. Al., 2010; Hettiarachchia et. Al., 2007).

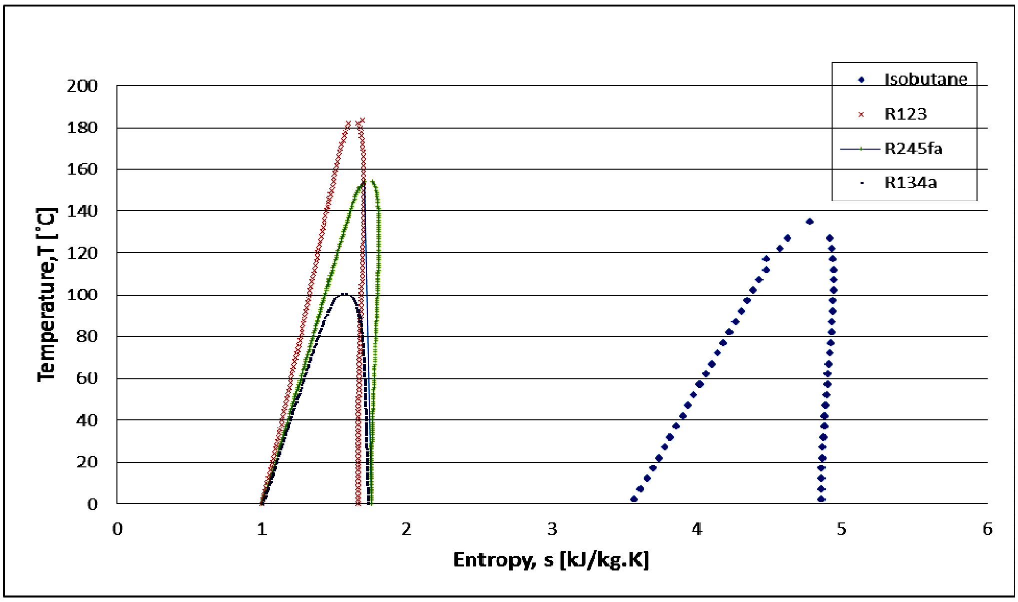

Figure 1 : Temperature versus entropy diagram for different refrigerants

Refering to Figure 1, R134a is not suitable as working fluid for the organic Rankine cycle. This is due to the saturated vapor line of R134a that has negative slope.

Therefore, the expansion process will occur in mixture phase, unless it is superheated first before entering the turbine. Furthermore, the critical temperature is lower than other organic fluids. On the other hand, isobutane, R123 and R245fa are suitable as working fluid as the saturated vapor line has positive slope. The evaluation of performance in organic Rankine cycle is based on temperature versus entropy diagram as shown in Figure 2a and 2b.

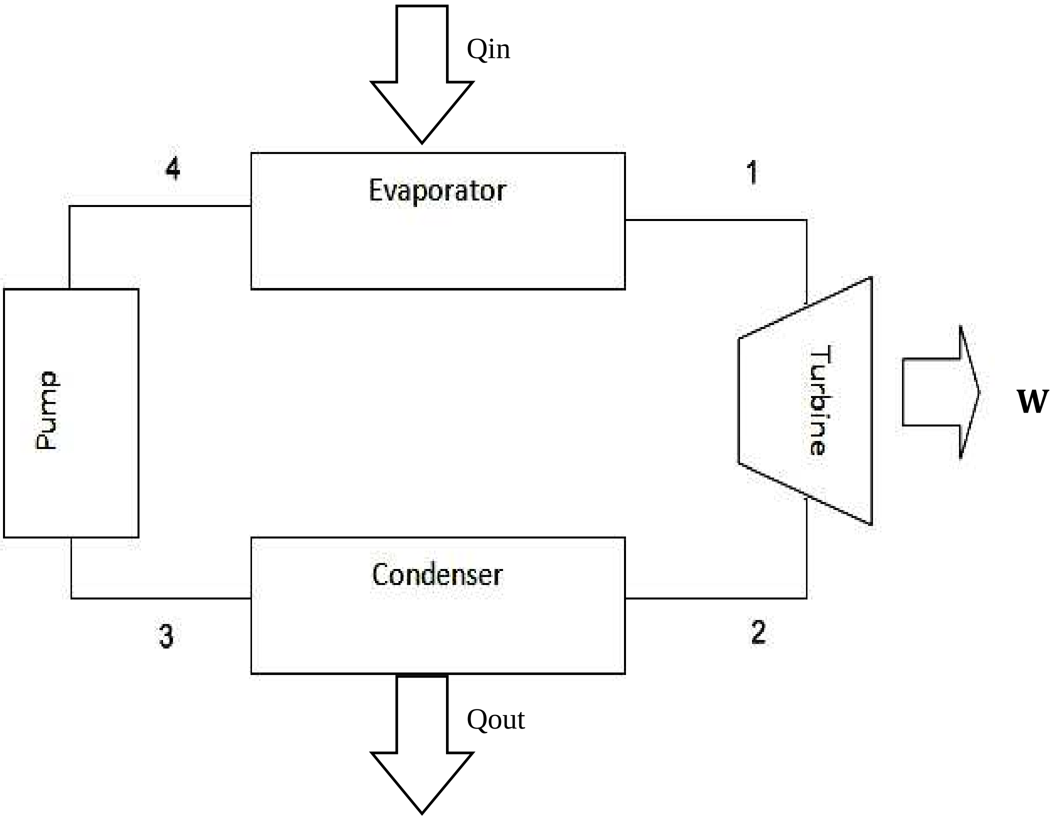

Figure 2a : Schematic diagram for organic Rankine cycle

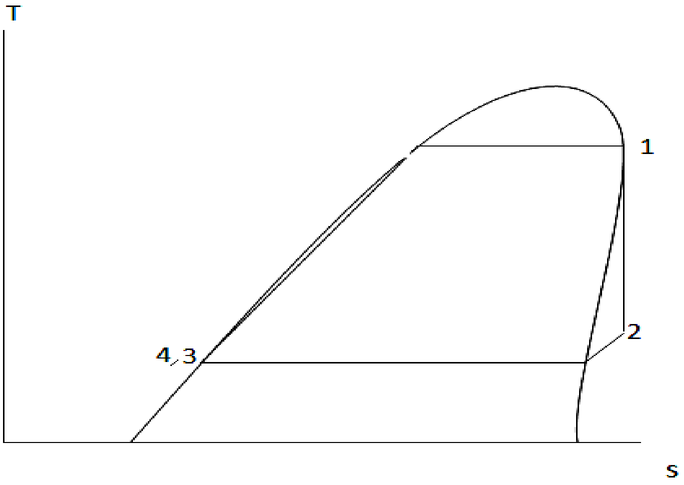

Figure 2b : T-s diagram for organic Rankine cycle

There are a few assumpations taken in this study. Firstly, the cycle used in the study is an ideal cycle. The turbine expansion is isentropic and pump work is considered negligible. The expansion in the turbine occur outside mixture phase, i.e. in the superheated region. The condenser temperature for all the organic Rankine cycles is set to 27°C, i.e. the ambient temperature. The reason for the assumptions is that we want to standardise the analysis so that one would know which cycle performs the best in terms of work output and efficiency. Following the assumptions, the mathematical formulations for organic Rankine cycle are as follows,

$$work \quad output = (h_1 - h_2) \tag{1}$$

$$heat \quad addition \quad in \quad evaporator = (h_1 - h_4) \tag{2}$$

$$efficiency = \frac{work \quad output}{heat \quad in} = \frac{h_1 - h_2}{h_1 - h_4} \tag{3}$$

2.0 ORGANIC WORKNG FLUIDS

2.1 Property of isobutane

Isobutane is a hydrocarbon and also known as R600a. Table 1 shows the thermophysical properties of isobutane, (Younglove and Ely, 1987; Younglove and Mclinden 1994).

Table 1 : Thermophysical properties of isobutane

Formula	C_4H_{10}
Molecular weight (g/mol)	58.12
Slope of saturated vapor line	Positive
Critical temperature (°C)	134.85
Critical pressure (MPa)	3.64

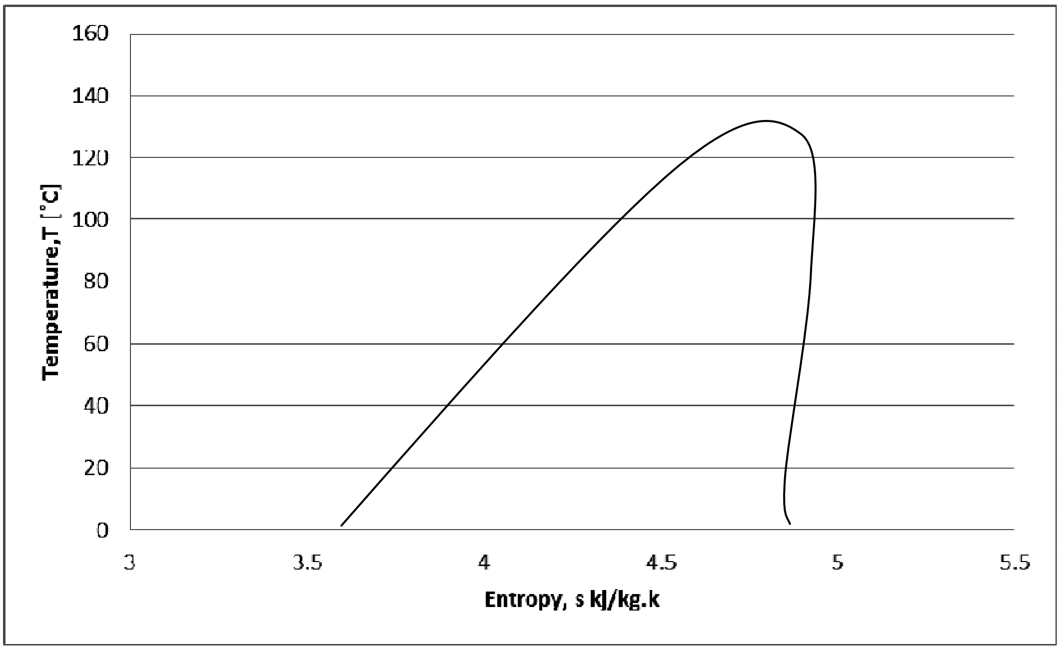

Figure 3 : T-s diagram of isobutane.

From Figure 3, it is found that the suitable point for the state 1(inlet of turbine), is at temperature equal to 107°C. This is the maximum temperature on the saturated vapour slope. The work and efficiency are calculated. The graph of work and efficiency versus turbine inlet pressure is plotted in order to analyse the performance of the cycle.

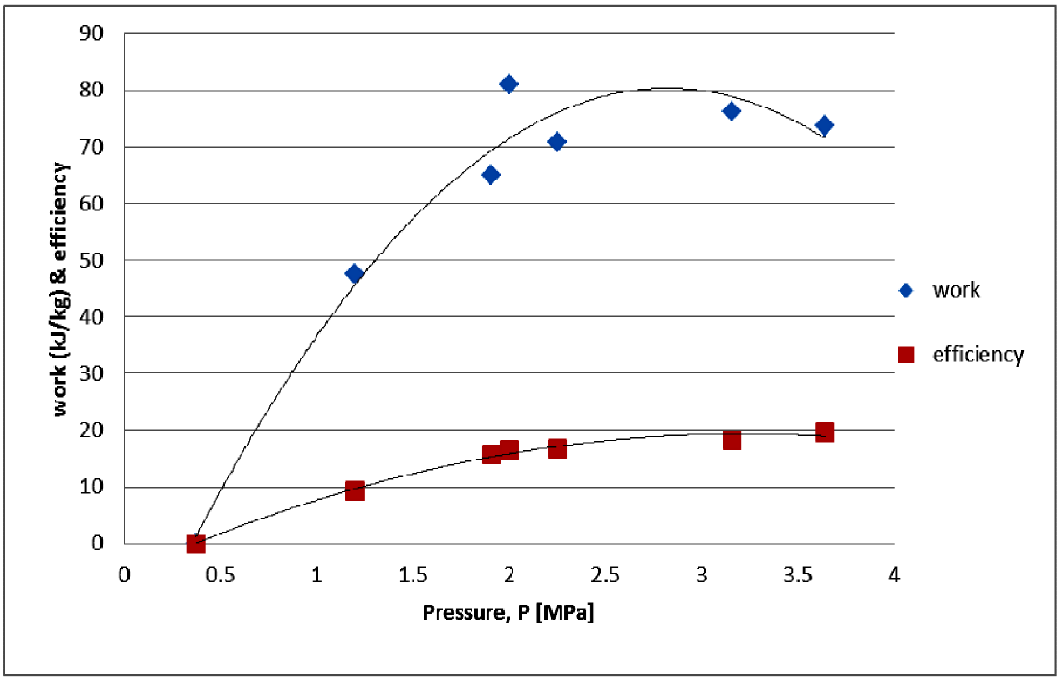

Figure 4 : Work and efficiency versus turbine inlet pressure of isobutane

From Figure 4, it shows that maximum work that could be obtained is 80.97 kJ/kg. Besides that, maximum efficiency that can be obtained from the system is 19.65%. Maximum work can be achieved at turbine inlet pressure equal to 2.86 MPa, while maximum efficiency can be achieved at turbine inlet pressure equal to 3.25 MPa.

2.2 Property of R123

Similarly for R123 the work and efficiency are calculated. This is important to see the performance of the organic Rankine cycle using R123 as working fluid. Table 2 shows the thermophysical properties of R123.

Table 2 : Thermophysical properties of R123

Formula	$CHCl_4 - CF_3$
Molecular weight (g/mol)	152.93
Slope of saturated vapor line	Positive
Critical temperature (C)	183.68
Critical pressure (MPa)	3.6618

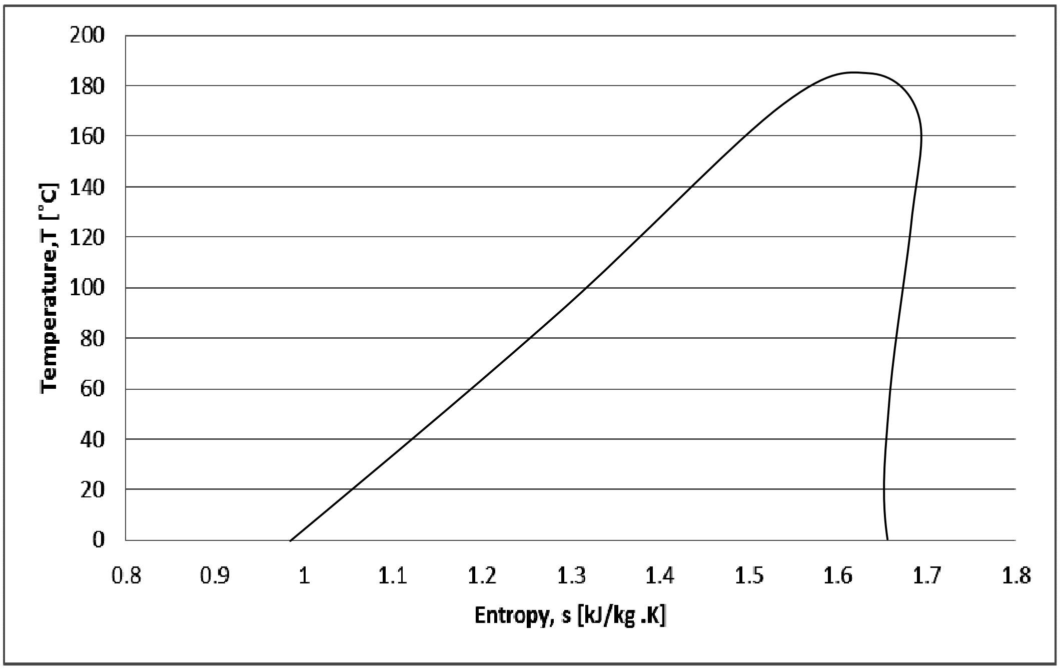

Figure 5 : T-s diagram of R123.

From Figure 5, it is found that the optimal temperature on the saturated vapour slope for the turbine inlet is at 150°C. The work and efficiency are then calculated. The graph of work and efficiency versus pressure is plotted in order to analyse the performance of the system.

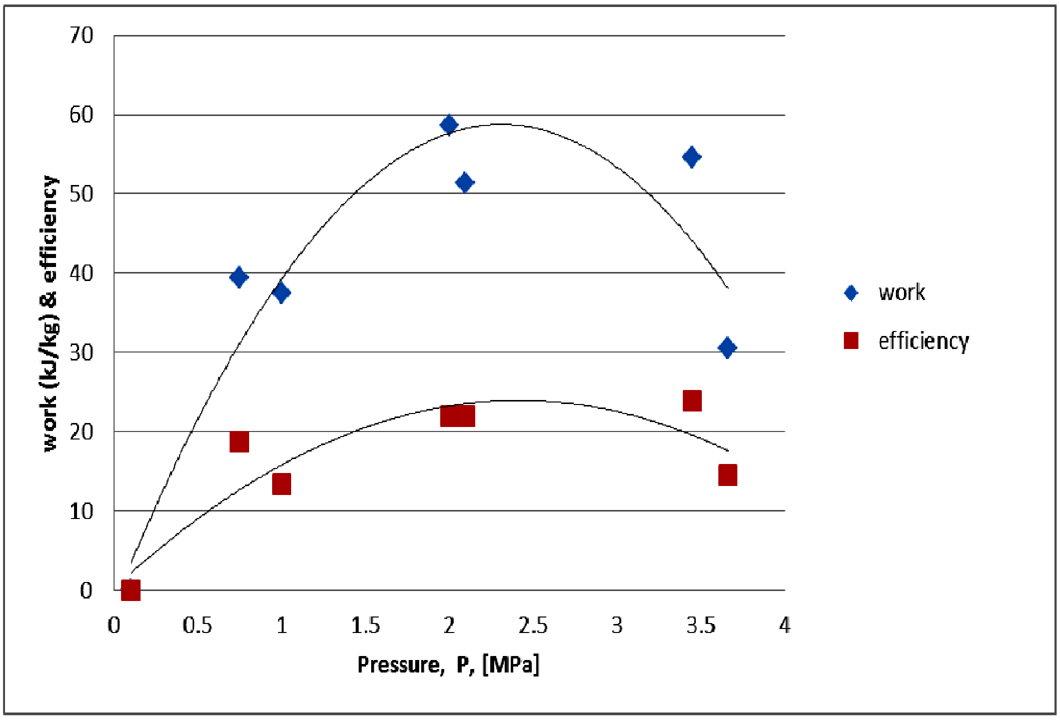

Figure 6 : Work and efficiency versuss turbine inlet pressure of R123

From Figure 6, it shows the maximum work that can be obtained is 58.63 kJ/kg. Besides that, maximum efficiency that can be reached for the cycle is 23.86%. Maximum work can be achieved at turbine inlet pressure equal to 2.34 MPa, while maximum efficiency can be achieved at turbine inlet pressure equal to 2.45 MPa.

2.3 Property of R245fa

Similarly with R245fa, work and efficiency are calculated. The performance of the organic Rankine cycle is then plotted on a graph. Table 3 shows the thermophysical properties of R245fa. The properties of R245fa is tabulated from software developed by Honeywell Genetron. (http://www51.honeywell.com/sm/genetron/contact-support/refrigerant-software.html)

Table 3 : Thermophysical properties of R245fa

Formula	$CF_3CH_2CHF_2$
Molecular weight (g/mol)	154.0
Slope of saturated vapor line	Positive
Critical temperature (C)	54.05
Critical pressure (MPa)	3.64

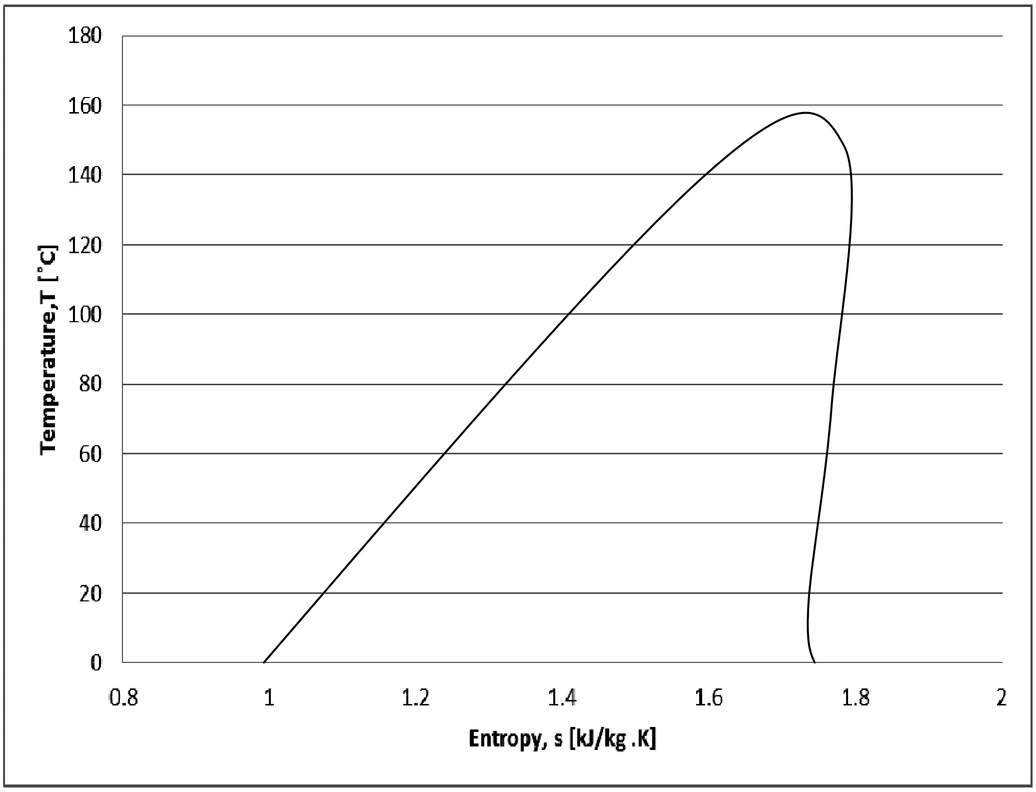

Figure 7 : T-s diagram of R245fa.

From Figure 7, it is found that the suitable point for the state 1 is at temperature equal to 130°C. The work and efficiency are calculated. The graph of work and efficiency versus pressure is plotted in order to analyse the performance of the system.

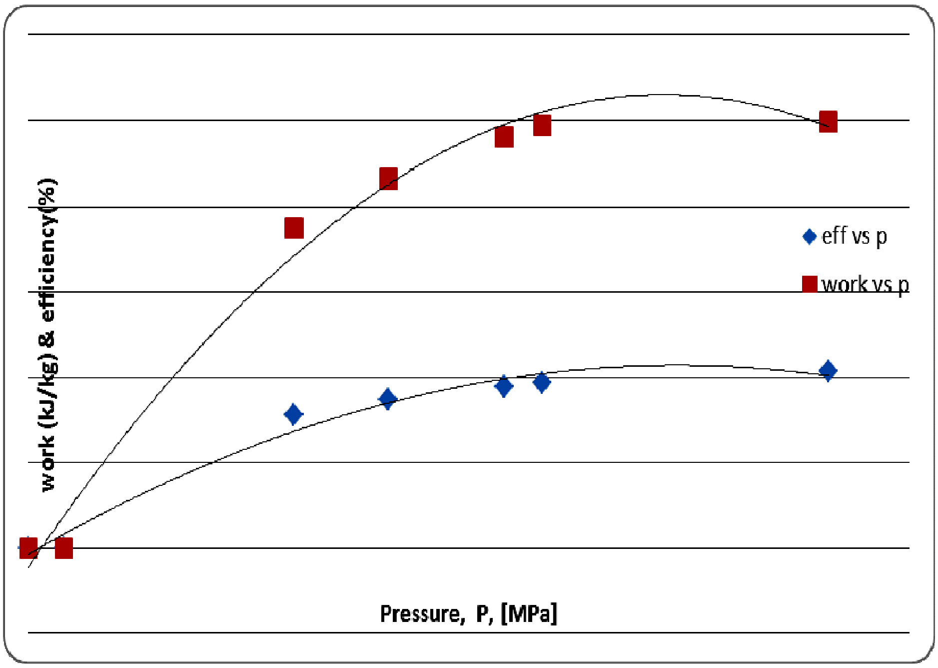

Figure 8 : Work and efficiency versus turbine inlet pressure of R245fa.

From Figure 8, it shows that maximum work that can be obtained is 53.36 kJ/kg. Besides that, maximum efficiency that can be reached for the cycle is 21.81%. The maximum work can be achieved at turbine inlet pressure equal to 2.8 MPa, while maximum efficiency can be achieved at turbine inlet pressure equal to 2.9 MPa.

3.0 COMPARISON OF EFFICIENCY AND WORK OF THE WORKING FLUIDS

The refrigerants are compared to analyse the performance of the system under optimal condition. The optimal condition is where the refrigerants start to expand from the maximum saturated vapour slope into the turbine superheated phase.

Table 4 : Comparison of different working fluids

Working fluid	**Isobutane**	**R123**	**R134a**	**R245fa**
Efficiency, (%)	16.83	22.01	15.08	19.30
Turbine inlet temperature, (°C)	102	150	98	130
Turbine inlet pressure (MPa)	2.25	2.10	3.82	2.34
Expansion condition region	superheated	superheated	mixture	superheated

Table 4 shows that under optimal condition, all the refrigerants expand in superheated region except R134a. In addition for optimal condition, the highest efficiency that can be obtained is 22.01%, using R123 as working fluid. R123 shows interesting characteristic, by achieving high efficiency with low pressure compare to other refrigerants. The T-s diagram for optimal condition can be seen in Figures 9, 10 and 11.

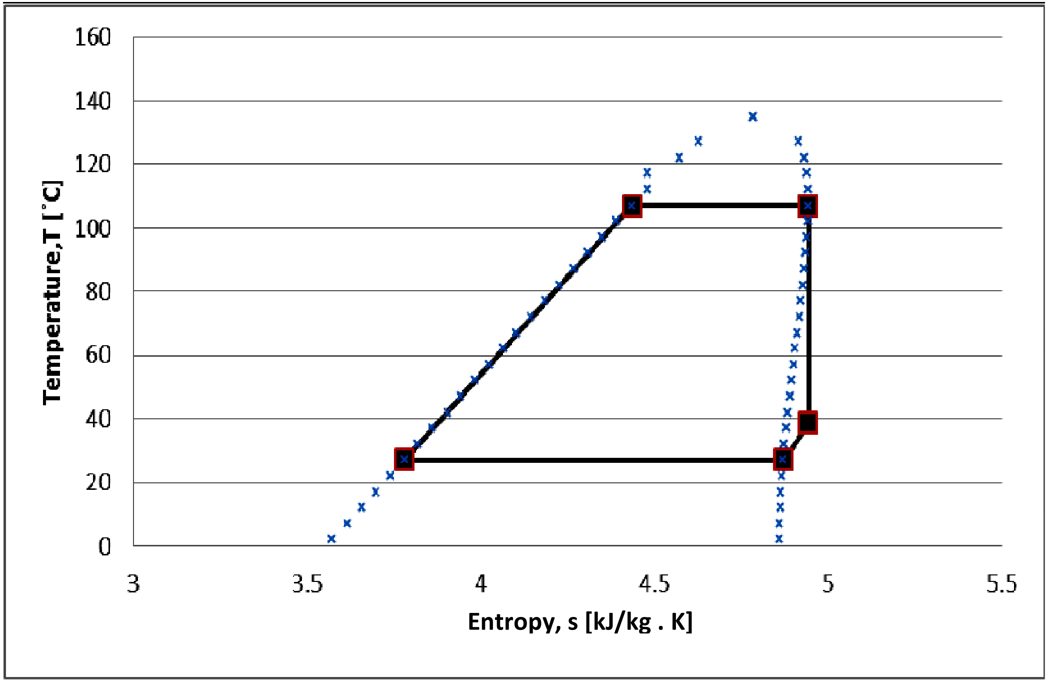

Figure 9 : T-s diagram of Isobutane for optimal condition.

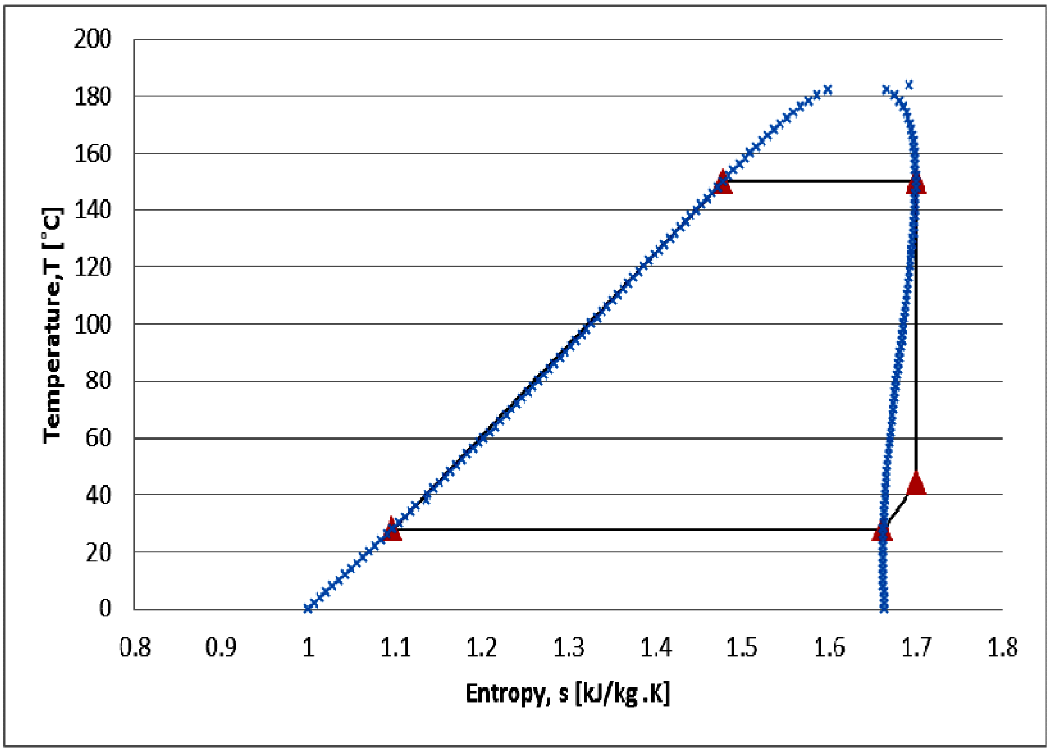

Figure 10 : T-s diagram of R123 for optimal condition.

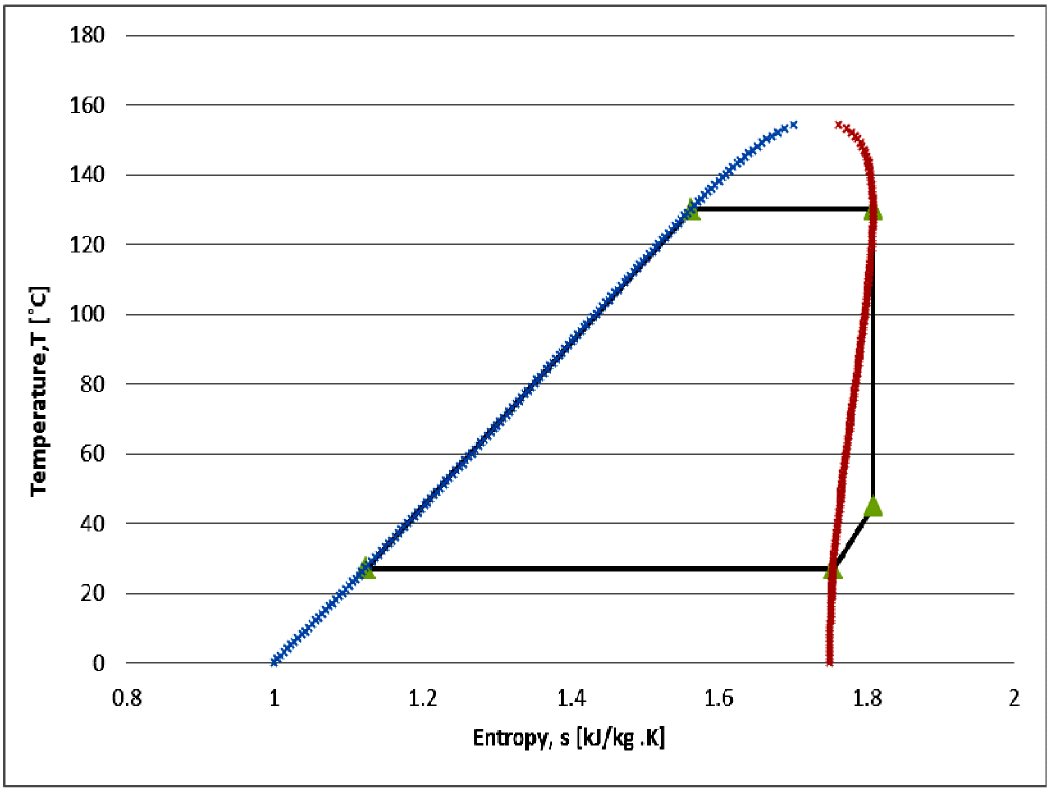

Figure 11 : T-s diagram of R245fa for optimal condition.

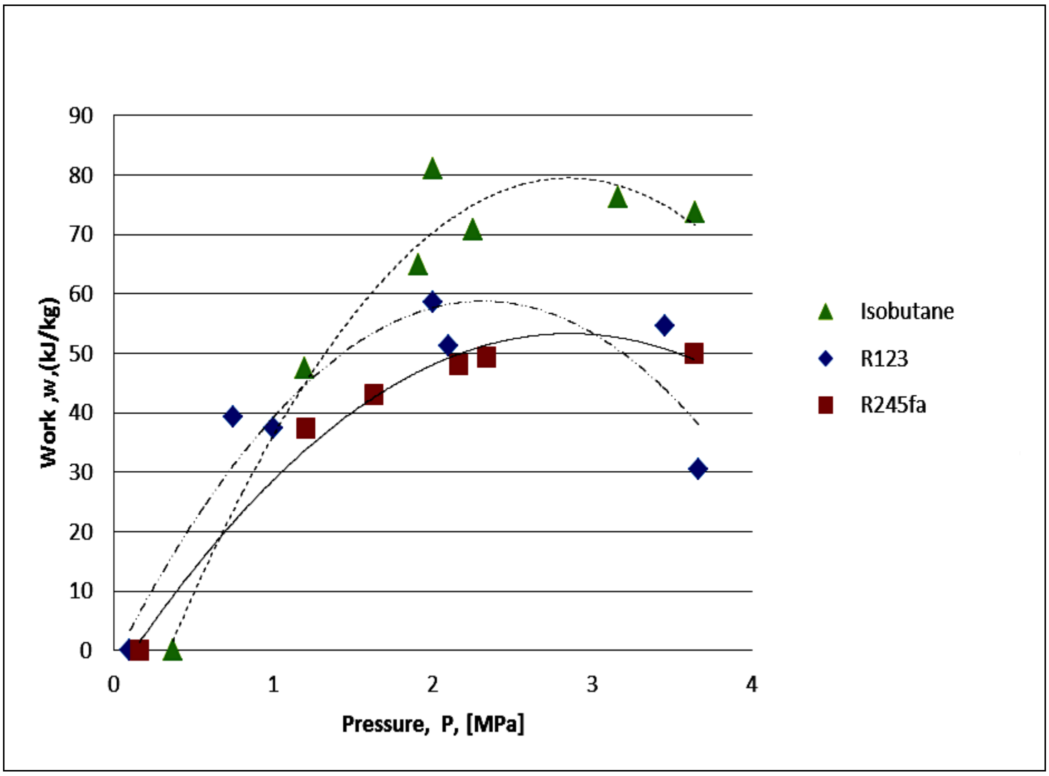

Figure 12 : Work versus pressure for comparison on different working fluids

From Figure 12, it can be seen that using isobutane as working fluid produces the most work. This is followed by R123 and R245fa. For low turbine inlet pressure of less than 1.0 MPa, R123 has the highest work produced, while for high turbine inlet pressure greater than 1.0 MPa, isobutane produces the highest work.

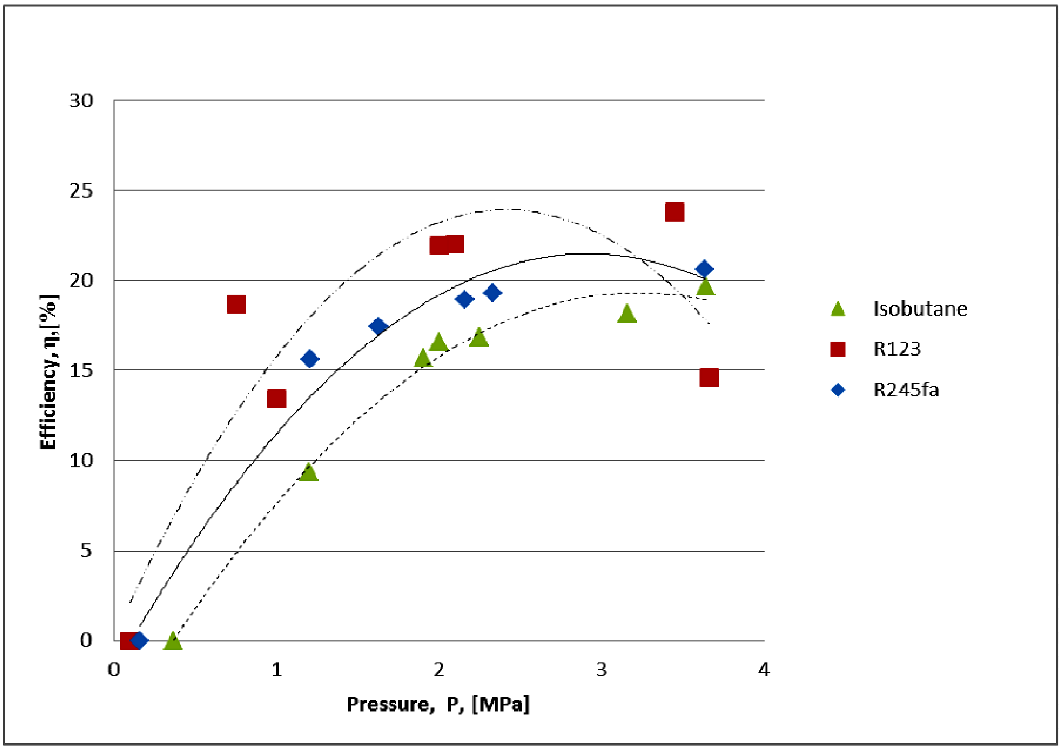

Figure 13 : Efficiency versus turbine inlet pressure for different working fluids

From Figure 13, it can be seen that R123 gives the highest efficiency. This is followed by R245fa and isobutane. For turbine inlet pressure less than 3.25 MPa, R123 has the highest efficiency. Beyond that range, R245fa has the highest efficiency than isobutane.

4.0 BINARY POWER CYCLES

From the results obtained in the organic Rankine cycles, condenser temperature of solar superheated steam Rankine cycle can be fixed. This condenser temperature is set about 10 - 15°C higher then the optimum turbine inlet temperature of the organic Rankine cycles. The performance is then evaluated. The performance evaluation is based on the work and efficiency of the binary cycles. The binary cycles is shown on the T-s diagram in Figure 14. The turbine inlet temperature for solar superheated steam Rankine cycle is fixed from the temperature of the parabolic solar trough collector which is equal to 400°C. According to to Lee, the capability of parabolic solar trough collecter is up to 750˚F or equivalent to 400˚C. (Lee, 2006). The condenser temperature is fixed at slightly higher than optimal turbine inlet temperature for organic Rankine cycle.

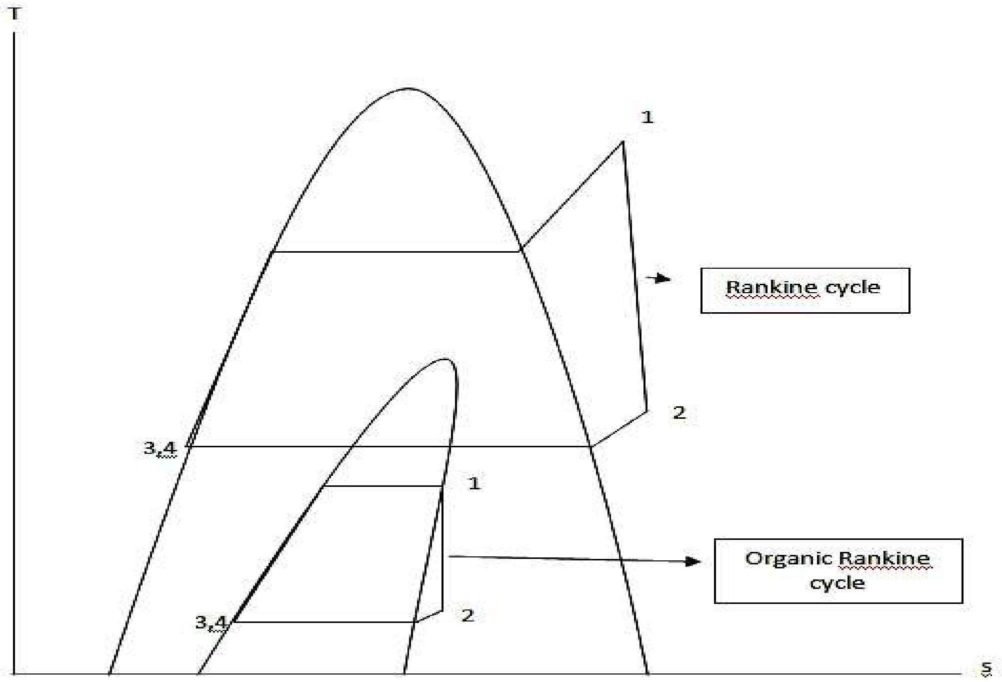

Figure 14 : T-s diagram for binary power cycle.

4.1 Binary Cycle with Isobutane

Results from organic Rankine cycle is used to determine condenser temperature for solar superheated steam Rankine cycle. Condenser temperature from Rankine cycle must be slightly higher than temperature of evaporator in organic Rankine cycle. For isobutane, condenser temperature for solar superheated steam Rankine cycle must be more than 107°C which is fixed at 120°C.

Table 5 : Combination of solar steam and isobutane power cycles

Steam					
State	**Temperature (°C)**	**Pressure (MPa)**	**Entropy (kJ/kg.K)**	**Enthalpy (kJ/kg)**	**State condition**
1	400	2	7.1292	3248.4	Superheated
2	120	0.199	7.1292	2706	Sat. Vapor
3,4	120	0.199	1.5279	503.81	Sat. Liquid
Work (kJ/kg)		542.4	**Efficiency (%)**		19.76

Isobutane					
State	**Temperature (°C)**	**Pressure (MPa)**	**Entropy (kJ/kg.K)**	**Enthalpy (kJ/kg)**	**State condition**
1	107	2.249	4.9429	389.17	Sat. Vapor
2	38.67	0.37	4.9429	318.35	Superheated
3,4	27	0.37	3.7799	-30.89	Sat. Liquid
Work (kJ/kg)		70.82	**Efficiency (%)**		16.87

From Table 5, the work obtained from solar superheated steam Rankine cycle is 542.4 kJ/kg with an efficiency of 19.76%. Combination of isobutane and steam can produce 613.32 kJ/kg of work.

4.2 Binary Cycle with R123

From the result of obtained in organic Rankine cycle for R123, condenser temperature must be fixed slightly higher than 150°C. This is meant for the heat transfer from solar superheated steam Rankine cycle to organic Rankine cycle. The condenser temperature of the solar superheated steam Rankine cycle is fixed at 165°C.

Table 6 : Combination of steam and R123

Steam					
State	**Temperature (°C)**	**Pressure (MPa)**	**Entropy (kJ/kg.K)**	**Enthalpy (kJ/kg)**	**State condition**
1	400	2	7.1292	3248.4	Superheated
2	165	0.314	7.1292	2791.59	Superheated
3,4	135.04	0.314	6.9769	567.91	Sat. Liquid
Work (kJ/kg)		456.81	**Efficiency (%)**		17.04

R123					
State	**Temperature (°C)**	**Pressure (MPa)**	**Entropy (kJ/kg.K)**	**Enthalpy (kJ/kg)**	**State condition**
1	150	2.099	0.8535	299.81	Sat. vapor
2	43.25	0.098	0.8535	247.95	Superheated
3,4	27	0.098	0.248	65.93	Sat. liquid
Work (kJ/kg)		51.86	**Efficiency (%)**		22.17

From Table 6, the work obtained from solar superheated steam Rankine cycle is 456.81 kJ/kg and the efficiency is 17.04%. Combination of R123 and steam can produce 508.67 kJ/kg of work.

4.3 Binary cycle with R245fa

For working fluid R245fa, the condenser temperature of the solar superheated steam Rankine cycle must be slightly higher then 130°C. The condenser temperature of the solar superheated steam Rankine cycle is fixed at 145°C.

Table 7 : Combination of steam and R245fa

Steam					
State	**Temperature (°C)**	**Pressure (MPa)**	**Entropy (kJ/kg.K)**	**Enthalpy (kJ/kg)**	**State condition**
1	400	2	7.1292	3248.4	Superheated
2	145	0.262	7.1292	2753.35	Superheated
3,4	128.96	0.262	1.6236	541.94	Sat. liquid
Work (kJ/kg)		495.05	**Efficiency (%)**		18.29
R245fa					
State	**Temperature (°C)**	**Pressure (MPa)**	**Entropy (kJ/kg.K)**	**Enthalpy (kJ/kg)**	**State condition**
1	130	2.335	1.0083	341.48	Sat. vapor
2	45	0.161	1.0083	292.14	Superheated
3,4	27	0.161	0.3226	85.84	Sat. liquid
Work (kJ/kg)		49.34	**Efficiency (%)**		19.30

Table 7 shows that 495.05 kJ/kg work can be obtained from the solar superheated steam Rankine cycle. On the other hand, the efficiency of the cycle is 18.29%. The binary cycle with R245fa and steam can produce a total work of 544.35 kJ/kg.

5.0 CONCLUSION

A parametric study to evaluate performance of solar thermal binary power generation cycles has been made. It consists of solar superheated steam Rankine cycle and organic Rankine cycle. For organic Rankine cycle, it is found that refrigerant R123 gives the highest efficiency among refrigerant R245fa, R134a and isobutane. Efficiency of R245fa is slightly lower then refrigerant R123. On other hand, isobutane has lower efficiency compared to R245fa, while R134a has lowest efficiency. Refrigerant R245fa, R123 and isobutane show good characteristic in the expansion process which occur in superheated region.

From combination of solar superheated steam Rankine cycle and organic Rankine cycle, it is found that combination of isobutane and steam produce the highest work compared to the steam combination with R245fa, and R123. In term of efficiency, for the solar superheated steam Rankine cycle, combination with isobutane, gave the highest efficiency.

The application of renewable energy in solar energy power generation still need further improvement to make it available for practical uses. The solar thermal steam superheated Rankine cycle shows promising potential in application The economic factor become the main constraint when organic Rankine cycle is applied due the cost of its working fluids and its system.

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