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SOLAR THERMAL ORGANIC RANKINE CYCLE AS A RENEWABLE ENERGY OPTION

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ABSTRACT

The objective of the paper is to study the feasibility of an Organic Rankine Cycle (ORC) driven by solar thermal energy as a renewable energy option for small and medium sized commercial usage, power generation of less than 10MW. ORC is principally a conventional Rankine Cycle that uses organic compound as the working fluid instead of water and it is particularly suitable for low temperature applications. Appropriate organic compound includes refrigerants and azeotropes. The ORC and the solar collector are sized according to the solar flux distribution in Malaysia. According to Malaysia Metrological Department, Kota Kinabalu has the highest yearly average of solar radiation in the country for year 2003, for this reason it is chosen for the location of study. The power generation system consists of two cycles, the solar thermal cycle that harness solar energy and the power cycle, which is the ORC that generates electricity. The solar thermal cycle circulates heat transfer fluid (HTF) in the cycle and harness thermal energy from the sun and transfers it to the organic compound in the ORC via a heat exchanger. Components in the power cycle or ORC include an ORC turbine for power generation, a condenser for heat rejection, a pump to increase the pressure and a heat exchanger. The HTF selected in this analysis is Therminol VP3, which is currently used for commercial solar thermal applications. For this research, 2 organic compounds were analyzed, R123 and isobutane. These two compounds are optimized for selection.

1.0 INTRODUCTION

Fossil fuel consumption in the recent years has been increasing and the burning of fossil fuel is said to be a major contributor towards global warming, air pollution and ozone depletion. Besides the environment, the fossil fuel price fluctuates considerably, with the price of the petroleum reaching as high as USD 53 [1]. Such a high price will take a toll on the economy of any country especially when Malaysia becomes a net importer of fossil fuel. Currently, 91.9% of Malaysia power generation uses fossil fuels. In recent years, Malaysia plans to reduce the reliance on fossil fuel by introducing renewable energy as the 5th Fuel in the 8th

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Malaysia Plan [2]. In the 8th Malaysia Plan, renewable energy sources are set to increase its power generation share to 5% of the total fuel mix in Malaysia.

Therefore, it is pertinent to explore renewable energy usage to generate electricity. For a conventional Rankine Cycle, it is efficient to employ low-grade heat source. Most renewable energy sources, for example solar and biomass are considered as low-grade heat sources because the heat energy supplied is much less compared to fossil fuel. Therefore in this study, it is proposed the use of solar thermal energy for sustainable power generation using the Organic Rankine Cycle (ORC). An example of a successful commercialized solar based power generation systems is the Solar Electricity Generation System (SEGS) in America, which generates 354 MW of electricity a year [3].

2.0 SYSTEM DESCRIPTION

2.1 Solar Thermal Cycle

Solar radiation can be divided into 2 components, direct radiation and diffuse radiation. Direct or beam radiation is the radiation that arrives at the ground without being scattered by clouds. The scattered radiation is known as diffuse radiation. The total radiation received; the sum of beam and diffuse, is called global radiation.

There are two main types of solar collectors available in the market, concentrated solar collectors and non-concentrated solar collectors. Concentrated collectors include the parabolic trough collector, the parabolic dish collector and the solar tower collector; while the flat plate collector is a non-concentrated collector. Concentrated collectors only harness direct radiation whereas non-concentrated collectors collect global radiation [4]. For Malaysia, more diffuse radiation is received as cloudy skies occur more frequently. Concentrated collectors have higher operating temperature range of between 500°C and 1200°C [5] while the non-concentrated collector, example the flat plate collector, operates at temperatures from 80°C to 180°C [3]. The absorber surface temperature, T_{ab}, for a concentrated collector is calculate using,

$$T_{ab}{}^{4} = (1-\eta)\frac{A_{ap}S}{A_{ab}\sigma} \tag{1}$$

where A_{ap} = aperture area
S = solar flux
σ = Stefan-Boltzman constant
A_{ab} = absorber area
η = collector efficiency

According to the Malaysia Metrological Department [6], Kota Kinabalu has a yearly average global radiation of 1.6 MJ/m^2. Diffuse radiation is calculated using correlations from Orgill and Hollands [4]. The direct solar radiation calculated for Kota Kinabalu is 1.01 MJ/m^2. By using Orgill and Hollands Correlation, diffuse radiation can be found as:

$$\frac{I_d}{I} = \begin{cases} 1.0 - 0.249k_T & k_T < 0.35 \\ 1.557 - 1.84k_T & 0.35 < k_T < 0.75 \\ 0.177k_T & k_T > 0.75 \end{cases} \tag{2}$$

where clear sky index, $k_T = \frac{I}{I_0}$

I is the measured global radiation and I_o is the calculated global radiation which is a function of latitude, day of the year and solar time for the location of study. Direct radiation is obtained by subtracting the diffuse radiation value from the global radiation.

2.2 Organic Rankine Cycle

Components that make up an ORC are similar to the conventional Rankine Cycle. The layout of an ORC is as shown in Figure 1. The efficiency of solar collectors had been rigorously studied, therefore the efficiency of various collectors are cross-referenced from other studies. Assuming an ideal cycle, the mathematical formulations for the components in an ORC are,

1) Feed pump to increase fluid pressure. Pump work, $W_P = v_3(P_4 - P_3)$
2) Condenser to reject heat to the environment, normally seawater. Heat rejected, $Q_{out} = \dot{m}(h_3 - h_2)$
3) Heat exchanger to transfer heat from heat source to the working fluid. The heat source is equals to the solar thermal energy collected by the collector. Heat received, $Q_{in} = \dot{m}(h_4 - h_1)$
4) Turbine for work conversion. Turbine work, $W_T = \dot{m}(h_1 - h_2)$
5) Cycle thermal efficiency, $\eta = \frac{W_{out}}{Q_{in}}$

Where $\dot{m}$ = mass flow
h = enthalpy
v = specific volume
P = Pressure

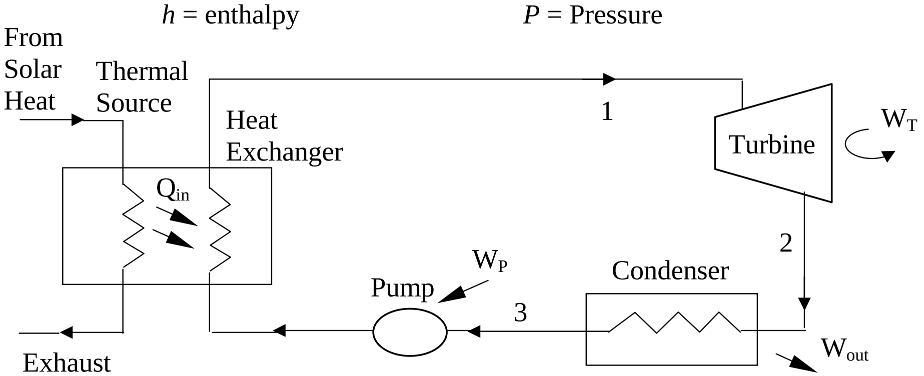

Figure 1: A simple diagram of ORC

Hung et. al has studied numerous organic fluids as a working fluid for Organic Rankine Cycle [7]. Two organic compounds are studied in this study, R123 and isobutane. These fluids are selected based on the criteria for an ideal Rankine Cycle fluid suggested by Nag [8]. R123, an isentropic fluid, was shown to deliver good results as per Yamamoto et. al [9]; while according to Larjola [10] isobutane is a dry fluid and is recommended for low temperature utilizations. These two working fluids are chosen to study the effects of different working fluids on the ORC. For R123, the thermodynamic properties were obtained from the Modified Benedict-Webb-Rubin (MBWR) equation of state from Younglove and McLinden [11]. For isobutane, the thermodynamic properties are also obtained from the MBWR equation of state which was tabulated by Younglove and Ely [12].

A parametric study was carried out to obtain the cycle efficiency of the ORC along the saturated vapor line in the subcritical region for R123 and isobutane. This was done in order to make the ORC's efficiency closer to the Carnot Cycle efficiency. Another important aspect is the limitation of the solar thermal collector's operating temperature. Cycles using these fluids will be optimized to deliver the highest work output and the highest efficiency along the saturated vapor line. The effects of turbine inlet temperature (TIT) on these fluids in the superheated region will be investigated at 2 pressure levels as compared to the optimized cycle. By increasing the TIT along the isobaric line, the working fluid will be superheated. Table 1 presents the thermophysical properties of R123 and isobutane.

Table 1: Thermophysical properties of R123 and Isobutane [13]

Parameters	**R123**	**Isobutane**
Chemical Formula	$CHCl_2 - CF_3$	C_4H_{10}
Molecular weight (g/mol)	152.93	58.125
Slope of saturated vapor line	Isentropic	Negative
Critical temperature (K)	456.831	407.85
Critical Pressure (MPa)	3.6618	3.64
Boiling point at 1 atm (K)	300.82	261.44
Maximum Pressure (MPa)	NA	35
Maximum Temperature (K)	NA	600

3.0 RESULTS AND DISCUSSION

The performance of R123 and isobutane as the working fluid for an ORC is analyzed. Computer programming using MATLAB is used to calculate and obtain the relevant thermodynamic data and various system performances. The effects of turbine inlet pressure (TIP) along saturated vapor line, the TIT in superheated region and the T-s diagram of ORC are discussed. Figure 2 depicts the graphical representation of R123 and isobutane in a T-s diagram. Unlike water, which has a negative saturated vapor line gradient, R123 and isobutane has a near-straight and positive gradient respectively. The gradient of the saturated vapor line will affect the system efficiency [14]. When the two fluids are compared, R123 has a much smaller enthalpy of vaporization but a higher critical point. A smaller enthalpy of vaporization means that less heat energy needed in vaporizing the fluid.

Figure 2: T-s diagram of R123 and Isobutane

3.1 Effect of Turbine Inlet Pressure along Saturated Vapor Line

The effect of TIP on the efficiency of the R123 and isobutane as the working fluid is shown in Figure 3. From the figure, it is shown that the efficiency for both fluids is a quadratic function of pressure. Relationship of work to pressure in the same graph also shows a quadratic line. Work and efficiency converted from ORC is a function of higher pressure for both fluids. Pressure point optimized work converted is near to the pressure point optimized at the maximum obtainable efficiency. As the pressure increases after the maximum point, less work is produced because the fluid will move further into the superheated region at the turbine outlet. This loss of work is due to the gradient of the saturated vapor line. More heat is rejected to the environment as the result of the gradient of the line. In power generation work output has priority over system efficiency if the difference in efficiency is not significant between the two maximum points. Referring to Table 2, the difference of efficiency obtained from optimized (Opt.) work cycle and optimized efficiency cycle for both fluids is only 0.3% although work output difference is about 0.4 to 2 kJ/kg.

A comparison between the two working fluids indicates that though R123 provides better overall thermal efficiency, isobutane gives better work output albeit at a lower efficiency. The difference between the maximum work outputs achieved by both working fluids is approximately 30 kJ/kg whereas the efficiency difference is 6%, as shown in Table 2. The condenser temperature or the minimum cycle temperature for R123 and isobutane is 28˚C. The common value for condenser temperatures is 24˚C, but the saturation pressure for R123 at 28˚C is equal to the atmospheric pressure. So, by fixing the temperature at 28°C, a vacuum condition is not needed in the condenser.

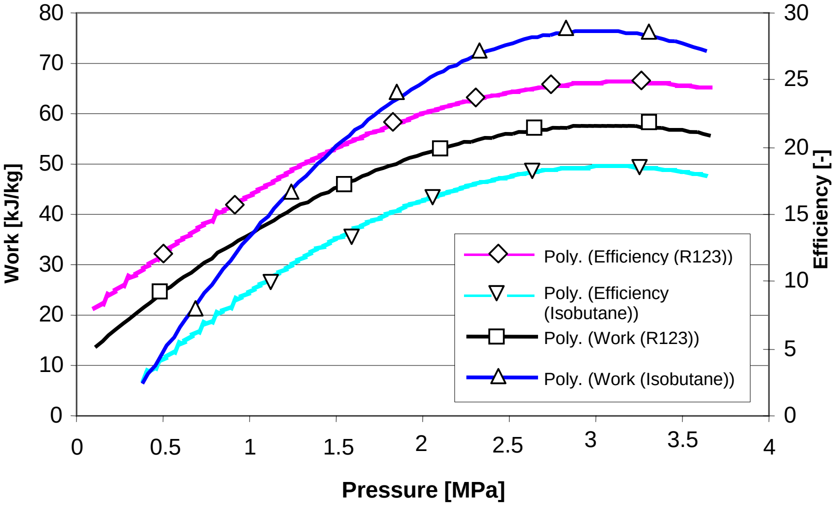

Figure 3: Work & efficiency vs. Turbine inlet pressure for R123 and Isobutane

The expansion ratio of R123 is nearly three times that of isobutene. The low volume flow ratio of isobutane is due to its lower molecular weight. The Carnot efficiency is evaluated at the same maximum and minimum working temperatures, the difference between the actual cycle efficiency and the Carnot efficiency is only from 6 to 8%. While, the difference in efficiency between a Rankine Cycle and a Carnot Cycle is normally in the range of 10 to 20%, at the same working pressure condition.

Table 2: Working fluid and conversion cycle characteristics for ORC System

Working Fluid	R123		Isobutane	
Condition	Opt. Work	Opt. Efficiency	Opt. Work	Opt. Efficiency
Min. cycle pres. [MPa]	0.10	0.10	0.38	0.38
Min. cycle temp. [˚C]	28	28	28	28
Max. cycle pres. [MPa]	3.40	3.54	3.16	3.40
Max. cycle temp. [˚C]	180	182	127	132
Compression ratio	34	35.4	8.32	8.95
Turbine expansion ratio	50.6	60.2	12.5	17.6
Isentropic work [kJ/kg]	58.99	58.54	77.65	75.78
Wettest vapor quality	0.84	0.78	0.95	0.86
Exhaust vapor quality	Superheated	0.98	Superheated	Superheated
Turbine mass flow [kg/s]	1	1	1	1
Cycle Efficiency [%]	25.63	25.90	18.57	18.85
Carnot Efficiency [%]	33.82	33.55	24.74	25.62

From Table 2, the term of “wettest vapor quality” is used. This term is to indicate the highest moisture content in the working section of the ORC turbine. When higher-pressure level of ORC is tracked along the saturated vapor line, it is found that as the pressure approaches the critical pressure, fluid expansion in the turbine will lead to higher moisture content as compared to the turbine outlet. This occurs due to the saturated vapor line curvature in the T-s diagram of the fluid, at higher pressures the gradient of the saturated vapor line changes from positive to negative.

To make sure that the vapor is dry in the turbine, because high moisture content will corrode the turbine, it is recommended that the TIP be set at the turning point of the saturated vapor line in the T-s diagram. The turning point is situated between the point of inflexion and the critical point. By changing the maximum cycle pressure, the efficiency and work output will drop to a lower value but the working fluid will be dry in the working section of the turbine. Table 3 shows the work delivered after correcting the pressure and temperature to the turning point. The choice of either choosing the maximum work, maximum efficiency or the corrected pressure will depend on economic factors. Others include the effect of wet vapor on the turbine blade, lifetimes of the turbine, cost of the turbine and materials involved. However, these economic considerations are beyond the scope of this study.

Table 3: Working fluid and conversion cycle characteristics at corrected pressure

Working Fluid	R123	Isobutane
Condition	Corrected Pressure	Corrected Pressure
Min. cycle pres. [MPa]	0.10	0.38
Min. cycle temp. [˚C]	28	28
Max. cycle pres. [MPa]	2.08	2.25
Max. cycle temp. [˚C]	150	107
Compression ratio	20.8	5.9
Turbine expansion ratio	71.2	7.0
Isentropic work [kJ/kg]	51.6	69.2
Exhaust vapor quality	Superheated	Superheated
Cycle Efficiency [%]	22.15	16.6
Carnot Efficiency [%]	28.88	20.72

3.2 Effect of Turbine Inlet Temperature in Superheated Region

The effect of superheating the working fluid is shown in Figure 4 for R123 and isobutane. For R123, efficiency is constant with the increase of turbine inlet temperature especially at higher pressures. Generally the efficiency declines with temperature increase although there is a slight efficiency increase at lower pressure. Therefore it is not attractive to increase the TIT to the superheated region for R123 because the increase in temperature does not increase the efficiency. With these two pressure levels plotted, performance at other pressure levels can be found using interpolation or extrapolation method.

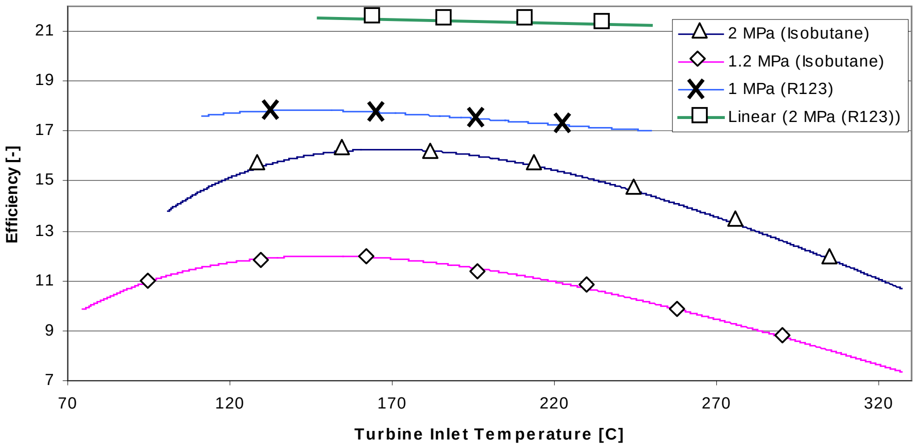

Figure 4: The effect of turbine inlet temperature on efficiency at superheated region for R123 and Isobutane

Isobutane ORC behaves quite similar to the R123 but the increase in efficiency is steeper with temperature increase at both pressures. After the maximum point, the drop of efficiency of the ORC is also steeper compared to R123. The increase of efficiency with temperature is as high as 2%. Therefore, for the isobutane ORC it is recommended to superheat within an allowable temperature limit at turbine inlet. The optimum temperature is around 150°C to 170°C depending on the inlet pressure.

3.3 Temperature-Entropy Diagram of Organic Rankine Cycle

Figures 5 and 6 show the T-s diagram for R123 and isobutane corresponding to the maximum work output cycle found in section 3.1. Superheating at 2 pressure levels as shown in section 3.2, for each working fluid was plotted in the same figures. From the T-s diagram, it is noticed that superheating ORC increases heat rejection and will results in lower efficiencies. Though superheating increases the efficiency for some fluids, example isobutane, but it will increase heat rejection. Therefore, superheating will only be attractive if improvements are made to re-use this heat rejection.

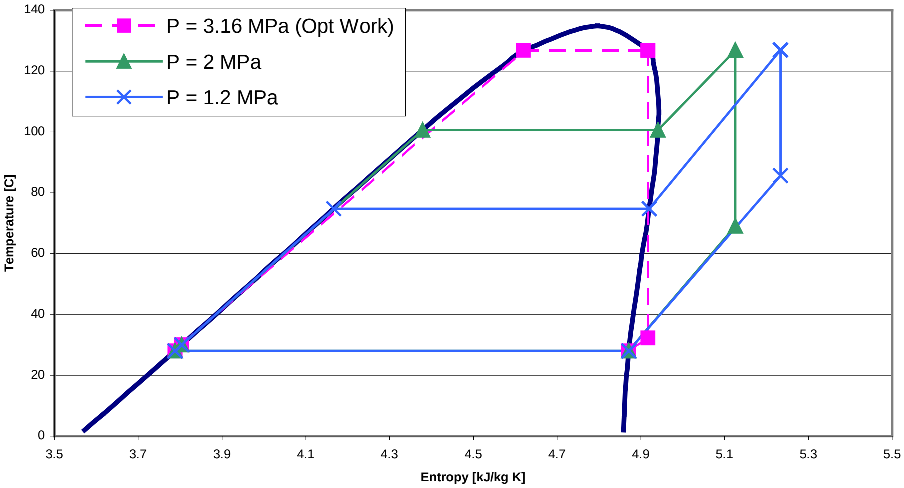

Figure 5: T-s diagram of ORC Isobutane at maximum work, P = 1.2 MPa & \ P = 2 MPa

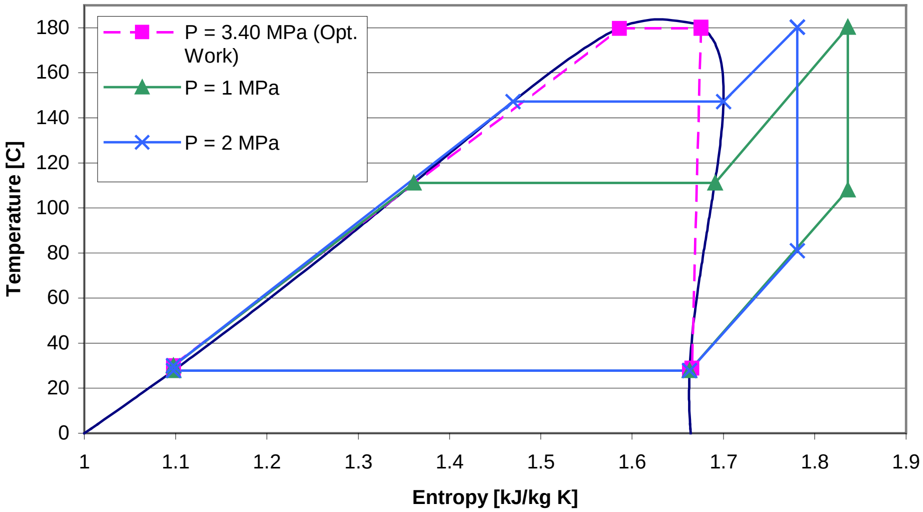

Figure 6: T-s diagram of ORC R123 at maximum work, P = 1 MPa & P = 2 MPa

4.0 CONCLUSION

In this study R123 and isobutane based ORC were examined for power generation. Work output and efficiency of the system along the saturated vapor line and superheating are investigated. Based on the analysis done, the following conclusions can be made:

1. R123 gives a higher thermal efficiency compared to isobutane, R123 efficiency ranges from 22 to 26% while isobutane ranges from 17 to 19%.
2. R123 is more suitable for higher temperature applications, while isobutane is preferable for lower temperature applications.
3. The ORC efficiency is closer to the Carnot efficiency with the difference being less than 10%.
4. The ORC efficiency for R123 is a weak function of turbine inlet temperature; as a result, superheating is undesirable.
5. Superheating isobutane for the ORC can increase the efficiency but there is an optimal temperature, from 150°C to 170°C.

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