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Journal of Advanced Research in Applied Sciences and Engineering Technology
ISSN (online): 2462-1943 | Vol. 4, No.1. Pages 29-46, 2016

Performance of Organic Rankine Cycle Using Biomass As Source of Fuel

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Abstract – *A simulation study has been done on Organic Rankine Cycle (ORC) with nine different working fluids in four different types of system configurations. An Organic Rankine Cycle is similar to Rankine cycle with the exception of using organic fluids for its working fluids. It is widely claimed to be more effective than steam Rankine cycle in low heat grade applications. The objective of the study is to study the performance of the system in conjunction with biomass thermal system by selecting the best working fluid and system configurations. The simulation is done using MATLAB and REFPROP 9.0 respectively. The selection of the best configuration is based on the thermal efficiency of the system. It is found that toluene is the best option in simple ORC system. In ORC system added with internal heat exchanger or recuperator, dodecane and propylcyclohexane are the better option compared to other fluids. All the organic fluids show improvements with addition of recuperator. For temperature range of 150^{o}C-300^{o}C, it is found that water is not effective compared to organics fluids. Superheating process shows a slight improvement in a system with recuperator, but no improvement in simple cycle. The highest thermal efficiency is found in Scenario D. The second best is Scenario C, followed by Scenario A and the most ineffective is Scenario B.*

Keywords: Organic Rankine Cycle, Biomass, Simulation, Organic Fluids

1.0 INTRODUCTION

With the world in concerns of fossil fuel depletion and global warming problems, more efforts have been done in order to utilize and optimize other alternative of energy sources. Like what is reported by the International Energy Agency (IEA) in its World Energy Outlook 2010 [1], currently fossil fuels are leading the energy distribution by far, with almost 81% of total energy demand. The highest contributor from renewable and sustainable resources is biomass with only 10% and this figure is the result of modern and traditional uses. Based on current energy scenario, IEA is optimistic to forecast that by 2020 and 2035, biomass is still dominant and the leader among the renewable energy resources.

By mean of renewable energy, biomass is green and does not increase the CO_2 level because the atmospheric CO_2 gas is captured in the process of photosynthesis. In Malaysia, the utilization of biomass as energy fuel can be considered too small compared to country's plantation and agricultural yield. In generating the electricity, the biomass is only contributing 2.4% from the total of 29,974 MW electrical generation [2]. Most of current biomass power plants in Malaysia are constructed in small to large scale (from 1MW to 15MW) [3].

Commonly, for large scale biomass power generation, the best effective way to generate power is co-fired with coals, that can achieve 45% efficiency. Meanwhile in solid biomass-fired plant, typically the fuel is combusted to generate steam using steam turbine (Rankine Cycle) [4]. Currently average size of existing bio-power plant is 20MW output with only average of 20% biomass-to-electricity efficiency [5]. Because of the small size of biomass power plant, Bain et al. [5] claimed that this small size of biomass power plant will cost more compared to larger power plant in term of capital cost per kilowatt-hour. Most of Organic Rankine Cycle (ORC) systems are used for low-grade heat source such as in geothermal and solar application, whereas this system also can be used in energy exploitation of agricultural residues and biomass where the heat source is medium temperature [6]. Hence, for a small scale bio-fired power plant, the ORC is the most promising solution to be applied. However to be used in medium and small system, higher molecular mass and low ebullition (critical temperature) working fluids should be used [7].

In Organic Rankine Cycle, the heat source level and the application itself play influence to the selection of the proper fluids and the parameters of operating conditions [8]. In previous studies, wide range of working fluids have been used including HCFC's, HFCs and Freon [9][10][11][12]. In the study by Yamamoto [10], they concluded that HCFC-123 is the best working fluids over water and methanol. However some of the organic working fluids used in previous studies are ozone depleting compound such as Freons and CFCs. In the other hand, HCFCs and HFCs are contributing to the green house effects [13]. In the other study, Mago [14] evaluated the performance of working fluid for a certain range of temperature of the heat source. They found that R113 is the optimal working fluid for the temperature above 430K. For the temperature between 380K and 430K they found R123,R245a and R245fa are better working fluids and whereas for the less of 380K application, isobutane is more appropriable [14].

In medium-grade heat source like in biomass application, the temperature of biomass-fired combustion process can reach up to 900^{o}C, so it is necessary to use thermal oil as the heat transfer medium between biomass boiler and ORC. This is because at this temperature the organic fluid in ORC can become chemically unstable [6]. In the other study, it is suggested that typical maximum temperature of organic fluid is 573^{o}C, in order to ensure its chemical stability [6]. In medium-grade heat source like in biomass application, most fluids for low temperature source cannot be adopted, this is because of high vapor pressure at these condensation temperature [6].

Based on previous studies, there is no yet specific guide available in order to develop an optimized Organic Rankine Cycle (ORC) system. The configuration of ORC is depending on the type of applications of the design, quality of heat source, and many other factors. Working fluid is one of the key factors in deciding an optimized ORC system. In order to develop a specific ORC plant, the working fluid is selected specifically for the condition of the system, because it gives better efficiency for a certain temperature range and could not suitable in other ranges [14].

The small scale power plant is proved to give lower efficiency and not economically feasible compared to large scale. However, the small scale is still needed to provide electrification to

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ISSN (online): 2462-1943 I Vol. 4, No.1. Pages 29-46, 2016

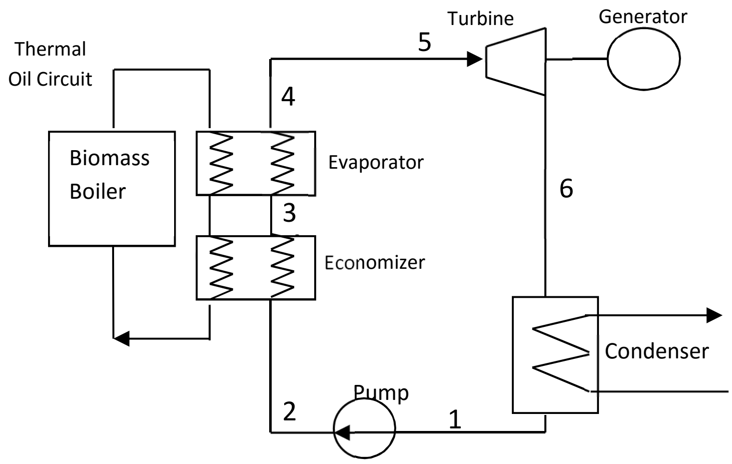
Malaysia off-grid area and also for Malaysia's agricultural usage near the agricultural industry fields. Therefore, it is the main reason to study the performance of ORC by selecting the most effective organic fluid in order to produce small scale ORC system for Malaysia's applications.

In this paper, the study is focussing on the performance of ORC system by selecting the best working fluid for small scale biomass power system with 3MWe output. The final selection is done based on the thermal efficiency criteria which is produced by the simulation using MATLAB algorithm and REFPROP liquid data.

2.0 METHODOLOGY

2.1 Organic Rankine Cycle (ORC) System

There are 4 scenarios of ORC system that will be simulated in this study. Those 4 scenarios are easily named as Scenario A, Scenario B, Scenario C and Scenario D. The first scheme of ORC which will be implemented in Scenario A and B are described in Figure 1.This scheme is a typical ORC system consists of pump, economizer, evaporator, turbine and condenser. The pump is used to supply the organic fluid to the economizer and evaporator (process 1-2) where the heat is transferred into the organic fluid (process 2-4) from the heat source which is thermal oil (suitable for biomass application due to high temperature [15]). Then the vapor of organic fluid will be expanded in the turbine to condensing saturated pressure(process 5-6). After it is expanded, the vapor of organic fluid will be condensed in condenser to become saturated liquid condenser (process 6-1).



Scenario A : Working fluid enters the turbine at saturated state.

Scenario B : Working fluid enters the turbine at superheated state (40°C more than evaporation temperature).

Figure 1: Plant layout for first scheme: Simple Organic Rankine Cycle without Internal Heat Exchanger (IHE) or recuperator.

In the second scheme for Scenario C and D (Figure 2), there is an additional of Internal Heat Exchanger (IHE) which also acts as recuperator. In this scheme, the heat from expanded organic vapor at turbine outlet is recovered to preheat the compressed organic fluid at process 2-9. It is necessary to implement the IHE as it is noted by Algieri [8], the IHE can improve the system up to 50% in term of electrical efficiency and power output.

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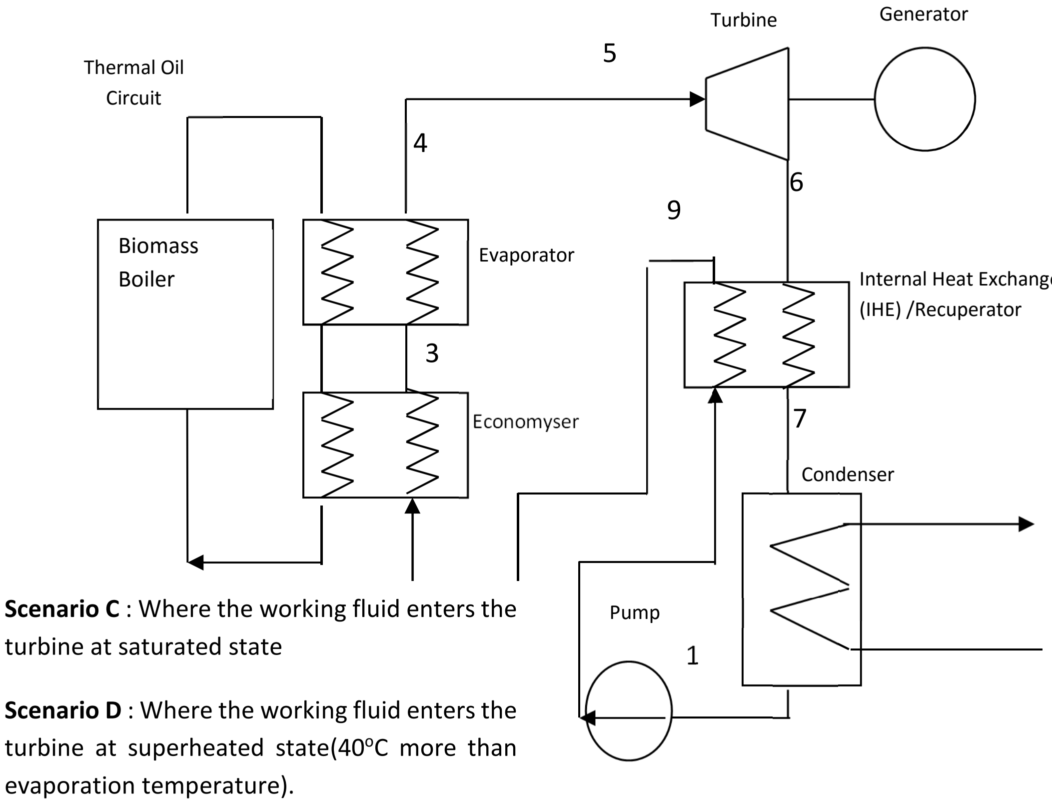

Figure 2: Plant layout for second scheme: Organic Rankine Cycle with Internal Heat Exchanger (IHE) or recuperator.

2.2 Thermodynamic Model

In order to simulate the system, a thermodynamic model has been developed to evaluate the performance of the system. The model is developed based on Algieri and Morrone [8], Drescher and D. Bruggemann [16] and Liu and his co-workers [17]. The model then will be integrated with REFROP database (Reference Fluid Thermodynamic and Transport Properties) in order to access the thermodynamic properties of the organic fluids. The general assumptions of the system are the fluid flow is in steady state condition, the pressure drops and head losses are neglected.

The power output of the system is determined to produce 3 MWe output, hence in the end of the simulations, the values of thermal and global efficiency η_{th} and mass flow rate, $\dot{m}$ (kg/s) will be simulated.

Thermal efficiency, η_{th} can be derived from [8] and [18]:

$$\eta_{th} = \frac{P_{net}}{Q_{in}} \tag{1}$$

Where P_{net} is the net power output and Q_{in} is heat power transferred into working fluid. The formula of P_{net} is represented by:

(2)

$$P_{net} = P_{turbine} - P_{pump}$$

To obtain the value of $P_{turbine}$ and P_{pump}as described in Eq(2), according to [8] they can be derived from this equation:

$$P_{turbine} = \eta_{is,t}\dot{m}l_{is,p} = \dot{m}l_t = \dot{m}(h_5 - h_6) \tag{3}$$

$$P_{pump} = \frac{\dot{m}l_{is,p}}{\eta_{is,p}} = \dot{m}l_p = \dot{m}(h_2 - h_1) \tag{4}$$

Where, $\dot{m}$ is organic mass flowrate , $\eta_{is,p}$ is isentropic effiency of pump, $\eta_{is,t}$ is isentropic effiency of turbine, $l_{is,p}$ is pump isentropic specific work, $l_{is,p}$ is turbine isentropic specific work, l_p is specific work of pump, l_t is specific work of turbine and h_i is specific enthalphy of that state.

In order to evaluate the heat power transferred into working fluid from thermal oil,Q_{in}, the equation of (5) can be used:

$$Q_{in} = \dot{m}q_{in} \tag{5}$$

Where q_{in} is evaluated from :

$$q_{in} = h_5 - h_2 \tag{6}$$

Where h_5 is specific enthalpy at turbine inlet and h_2 is specific enthalpy at turbine outlet. However in second scheme system where IHE is used, the q_{in} is derived as

$$q_{in} = h_5 - h_9 \tag{7}$$

Where h_5 is specific enthalpy at turbine inlet and h_9 is specific enthalpy of compressed organic fluid after preheated by IHE.In order to perform thermodynamic analysis, h_9 state should evaluated and this can be related to IHE efficiency equation, η_{IHE} [19].

$$\eta_{IHE} = \frac{h_9 - h_2}{h_6 - h_7} \tag{8}$$

According to [8], the specific enthalpy at state 7 can be analyzed from its relation with the temperature at state 7, T_7 and this temperature is related by:

$$T_7 = T_{cond} + \Delta T_{\mathrm{IHE}} \tag{9}$$

whereT_{cond} is condensation temperature.

For the purpose of this system, general thermal efficiency,η_{th} equation becomes:

$$\eta_{th,without\ IHE} = \frac{(h_5 - h_6) - (h_2 - h_1)}{(h_5 - h_2)} \tag{10}$$

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$$\eta_{th,IHE} = \frac{(h_5 - h_6) - (h_2 - h_1)}{(h_5 - h_9)} \tag{11}$$

2.3 Simulation

In order to evaluate performance of the subcritical saturated organic rankine cycle (ORC) with and without Internal Heat Exchanger (IHE), the simulations will be done in MATLAB environment co-integrated with REFPROP, a thermodynamic database program that is developed by National Institute of Standards and Technology (NIST). All the mathematical calculations and data evaluation will be performed in MATLAB.

The simulations will be performed for 9 different working fluids in 4 different scenarios, with variation of evaporating temperatures, T_{eva} and with different evaporating saturated pressure P_{eva}. The values of evaporating saturated temperature are depending on the evaporating temperature and type of working fluid itself. The assumptions that will be adopted in the simulation are :

i. Steady state condition
ii. Pressure drops and heat losses in the system components have been neglected
iii. The condensing temperature is fixed at 373K (100°C)
iv. The electrical power output is fixed at 3MWe.
v. Turbine isentropic efficiency,$\eta_{is,t}$ and Pump isentropic efficiency$\eta_{is,p}$ is 80%.
vi. Internal Heat Exchanger efficiency, η_{IHE} is 95%
vii. Electrical generator efficiency, η_{IHE} is 90%
viii. Efficiency of boiler,η_{Boil} is assumed to be 70%.
ix. Efficiency of thermal oil system,η_{oil} is assumed to be 90%.
x. The organic fluid enter turbine inlet is perfectly at state of saturated vapor.
xi. Organic fluid enter the pump is perfectly at state of saturated liquid.
xii. The temperature difference in Internal Heat Exchanger (IHE),ΔT_{IHE} is 10K.
xiii. The temperature difference of superheated state and saturated vapor,$\Delta T_{superheat}$ is 40°C

The flow of simulation process is illustrated in Figure 3. The first variable to be controlled is type of working fluids. Then, the value of T_{eva} is key in to solve the equations by obtaining the thermodynamic properties from REFPROP until the results of thermal efficiency η_{th} and mass flow rate are obtained. Then, this step repeated by using other T_{eva} until it reaches maximum temperature T_{max}, with interval of 20K increment. The maximum temperature of working fluid T_{max} is different to each other, depending on its type as discussed in previous subchapter. Next, those steps mentioned will be iterated with 9 different working fluids. The result of simulation using Toluene as working fluid will be validated with the results obtained by Algieri and Morrone [8]. In the end, the results will be analyzed in order to analyze the configuration of the system in order to produce 3MW output.In prediction, theoretically the working fluids with higher T_{boil} will give better thermal efficiency η_{th}, and based on ranking from the most effective to the least effective working fluid,the ranking prediction sequences are Dodecane, Propylcyclohexane, OMTS, Nonane, Toluene, water ,Cyclohexane and R113 respectively.

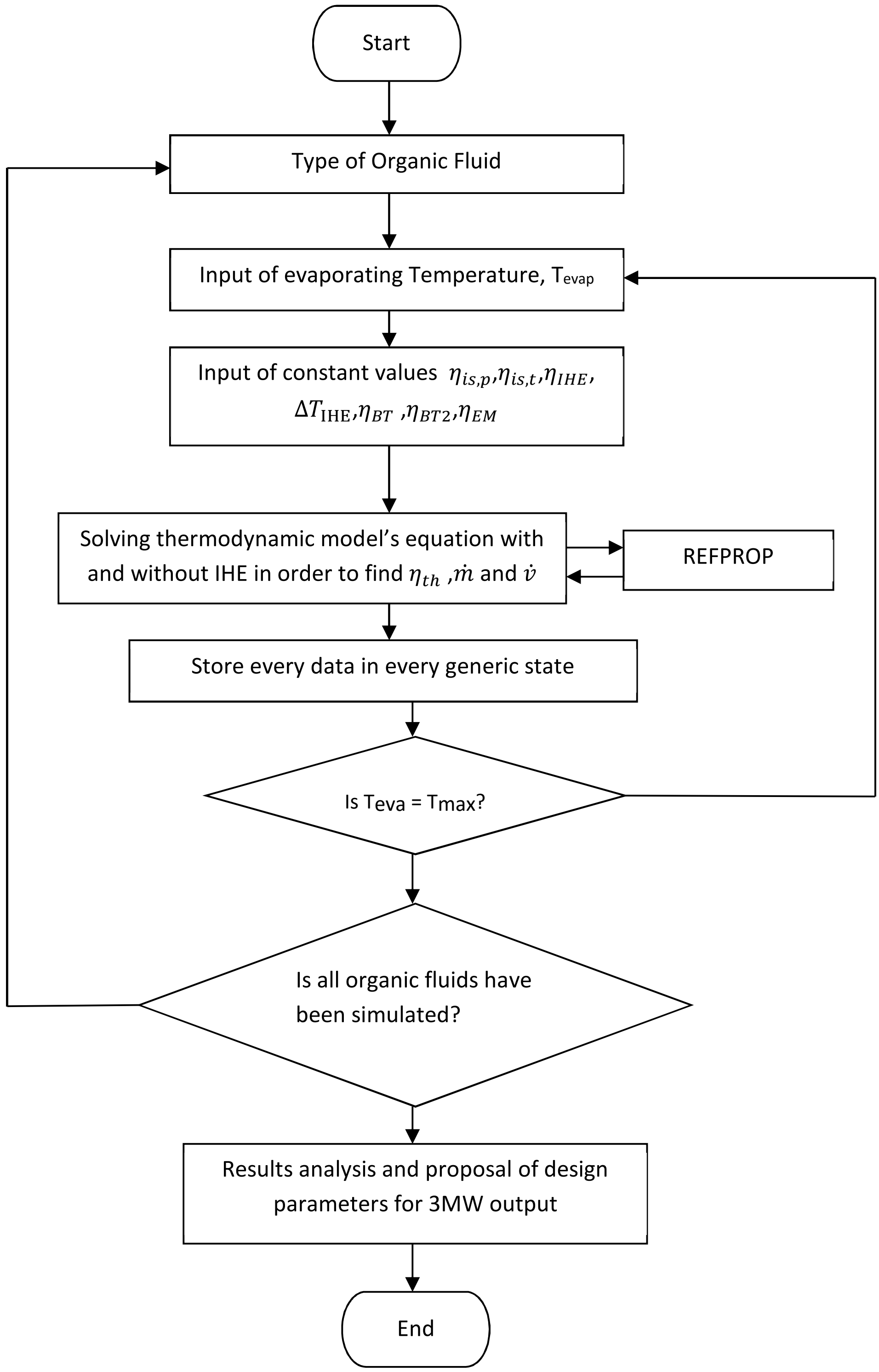

Figure 3: Flow chart for Simulation of Subcritical ORC System.

3.0 RESULTS AND DISCUSSION

3.1 Thermal Efficiency vs Vaporization Temperature

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The simulation result was validated by comparing the simulation results with the results obtained from Algieri and Morrone [8]. The three working fluids used in the comparison are Toluene, Cyclohexane and Decane. All the system setup parameters are set to the same as used by [8] as discussed in previous section. The comparisons have been done for both system setups; the simple ORC and the ORC with Internal Heat Exchanger (IHE).

As shown in Figure 4, the line plots for the simulation results of ORC without IHE are seem to match with the line plots of validation results. The results obtained from the simulation with IHE are also visually similar to the validation results illustrated in the graph of Figure 5.

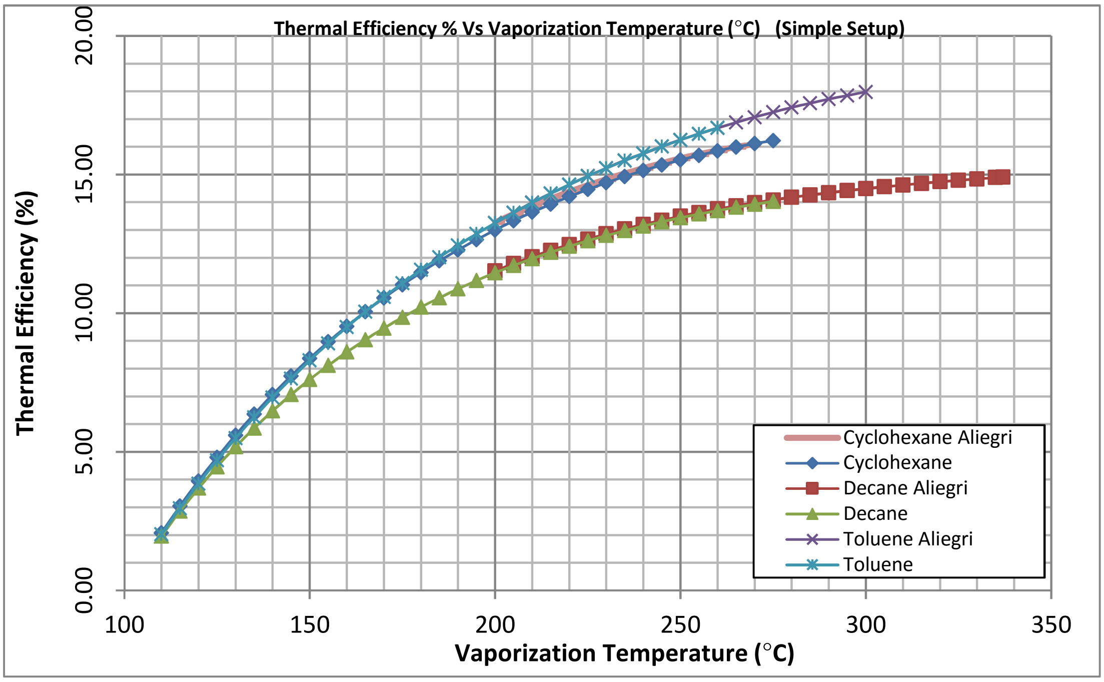

Figure 4: Graph of Thermal Efficiency (%) Vs Evaporation Temperature (C) for a ORC system without IHE.

Based on the Figure 4 and Figure 5 above, it can be concluded that the results obtained from the simulation studies are closely matched with the results obtained from [8]. Regarding to this validation, the simulation studies have been proceeded with using the other 6 workings fluids which are Dodecane, Propylcyclohexane, Octamethyltrisiloxane (OMTS), Nonane, R113,and water. Generally, the averages of percentage of differences are below 1%. As summary of the validation, this study can proceed with other working fluids as the subject of interest of study.

The simulation results have been obtained from 4 scenarios of ORC systems which are;

i. Scenario A : Simple ORC system with Saturated Vapor at the inlet of turbine;
ii. Scenario B :Simple ORC system with Superheated Vapor (additional 40oC from saturation vapor) at the inlet of turbine;
iii. Scenario C: ORC system with Internal Heat Exchanger (IHE) with saturated vapor at turbine;

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Scenario D: ORC system with IHE with superheated vapor(additional 40oC from saturation vapor) at turbine.

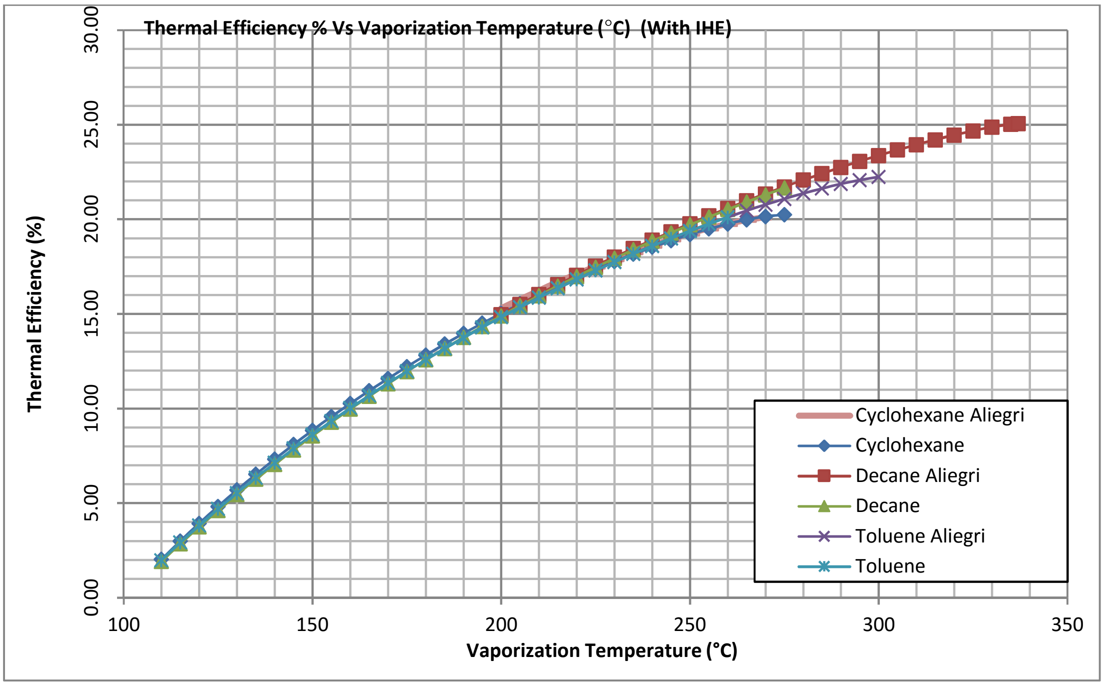

Figure 5: Graph of Thermal Efficiency (%) Vs Evaporation Temperature (C) for a ORC system with IHE.

Figure 6 shows the summary of Thermal Efficiency (%) vs Vaporization Temperature (°C) for all scenarios. The increase of thermal efficiency compared to Scenario A are 24.35%, 61.43%, 23.75%, 65%, 58%, 57.1%,83.35% and 9.60% respectively to Cyclohexane, Decane, Toluene,Dodecane, Nonane, Propylcyclohexane, OMTS, and R113. Among 8 organic working fluids, OMTS shows the highest performance rise, 83.35% increment. All of the organic fluids(except R113) give better thermal performance than water in range of 150ºC to 300ºC. The ranking of working fluids in this scenario is also changed. The ranking order is topped by Dodecane (23.76%), Propylcyclohexane (23.70%), Decane (23.31), Nonane (22.80%), Toluene (22.25%), OMTS(20.48%), Cyclohexane(20.17%) and R113(12.56%). Although R113 shows the rise of performance in scenario C, but because of its maximum temperature limit (200ºC) make it(12.56%) sits at the bottom of ranking of thermal performance and also performs poorer than water.

As in Scenario D, the system is almost the same as Scenario C, but the only different is the superheated vapor is used (with additional of 40 ºC) instead of saturated vapor. As shown by Scenario B, the superheating process only shows negative impact to the thermal performance of organic fluids, however it is oppositely happened for Scenario D. By using superheated vapor in the system with IHE, it promotes more thermal efficiency of ORC system. The ranking of thermal performance also changed a little bit compared to Scenario C where Propylcyclohexane(25.30%) tops the rank followed by Dodecane(25.06%), Toluene(24.95%),

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Decane(24.92%), Nonane(24.73%), Cyclohexane(23.74%), OMTS(22.37%) and R113(15.28%). Same as in Scenario C, all organic fluids(except R113) in Scenario D perform better than water.The percentage difference of performance between organic fluids and water are Propylcyclohexane (+42.94%), Dodecane (+41.58%), Toluene (+40.96%), Decane (+40.79%), Nonane (+39.72%), Cyclohexane (+34.12%), OMTS (+26.38%) and R113 (-13.67%).

3.2 Thermal Efficiency Vs Evaporation Temperature

Figure 7 shows the graph of Thermal Efficiency (%) Vs Evaporation Pressure (kPa) for the evaporation temperature range of 150°C to 300°C. The operating pressure (evaporating pressure) is shown by the x-axis for each of line corresponds to its thermal efficiency. Generally, water need higher pressure to be operated compared to organic fluids. As example, the highest thermal efficiency of water (η_{th}=17.34%) have to be operated at 8.6MPa where as for Toluene to get about the same efficiency is just to be operated at 2.4MPa.

The operating pressure will directly affect the size of plant and also directly related to the component cost. Power plants operated at high pressure also must have human operators to monitor the pressure system, where as in low pressure system, the automatic computer-control can replace human responsibilities. Operation monitoring contributes to the rise of operation cost and for that ORC has better efficiency of operation cost that steam system. It is more feasible if the pressure is low as possible but at the same time having high thermal efficiency. In this Scenario A, the evaporating pressure for Dodecane is the lowest compared to other working fluids, however its thermal efficiency is not good as Toluene and Cyclohexane in higher evaporating pressure.

In scenario B, the pattern of graph thermal efficiency (%) vs Evaporation Pressure (kPA) is almost similar to the graph in Scenario A. However, as mentioned earlier in Thermal efficiency (%) Vs Evaporation Temperature, the organic fluids in Scenario B have slightly lower thermal performance compared to the results obtained in Scenario A. The usage of water in rankine cycle needs more pressure for every value of thermal efficiency compared to organic fluids, except R113 working fluid. R113 performs poorer than water even in higher evaporating pressure for Scenario A and B.

For the Scenario C, where the ORC system is added with IHE, all organic fluids (excludes R113) produce higher thermal efficiency with lower evaporating pressure compared to water. In this scenario, R113 still lack of performance regarding to other working fluids including the water. Dodecane tops other organic fluids with thermal efficiency of 23.76% at only 527.74 kPa of evaporating pressure.It is obvious Dodecane is the best option for this type ORC system where it gets highest thermal efficiency at the lowest evaporating pressure. From the graph, the second best option is Propylcyclohexane, where it produces 23.76% of thermal efficiency at about twice(1385.84kPa) of Dodecane's evaporating pressure. Water is completely out of match where it has to be operated at pressure of about 43 times larger than Dodecane to get the same thermal performance.

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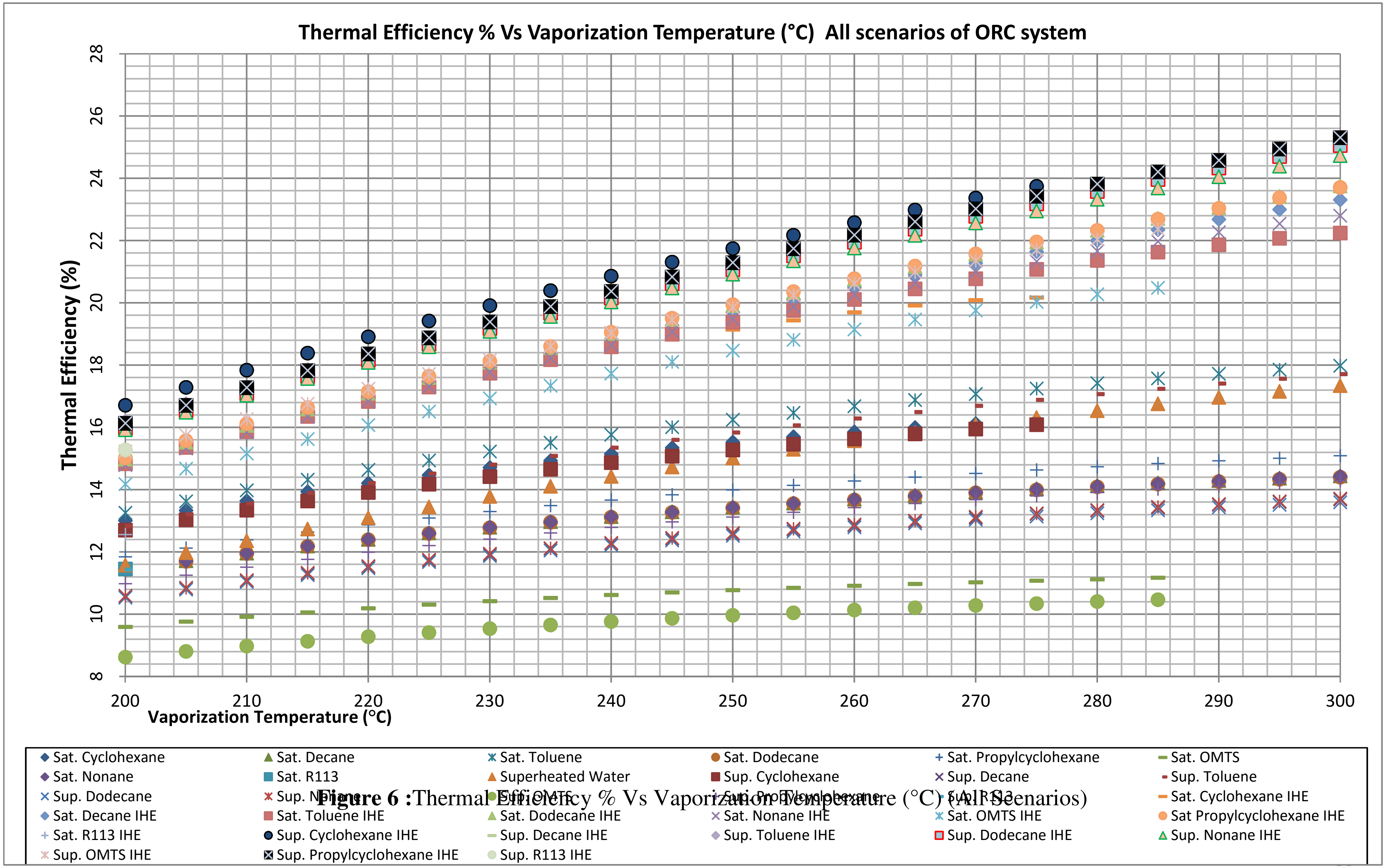

Figure 6 : Thermal Efficiency % Vs Vaporization Temperature (°C) (All Scenarios)

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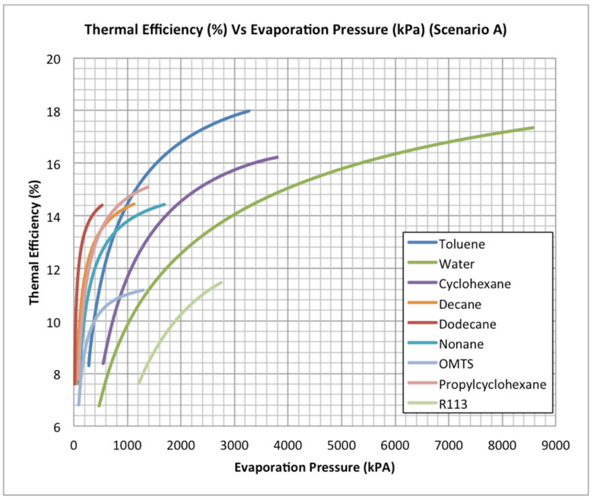
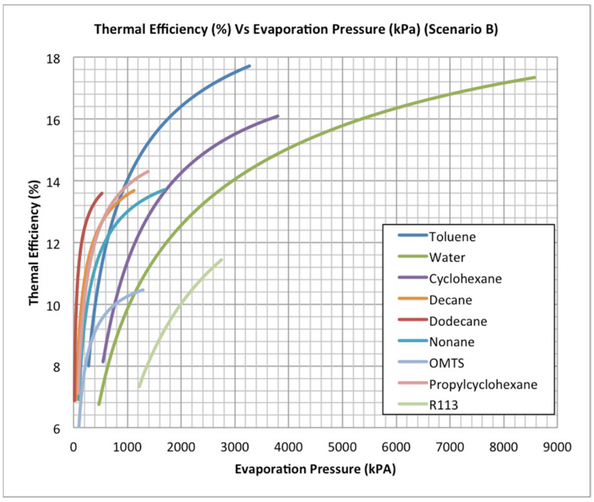
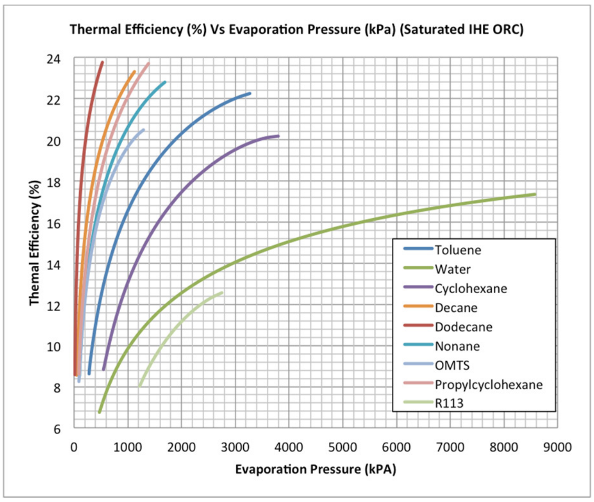


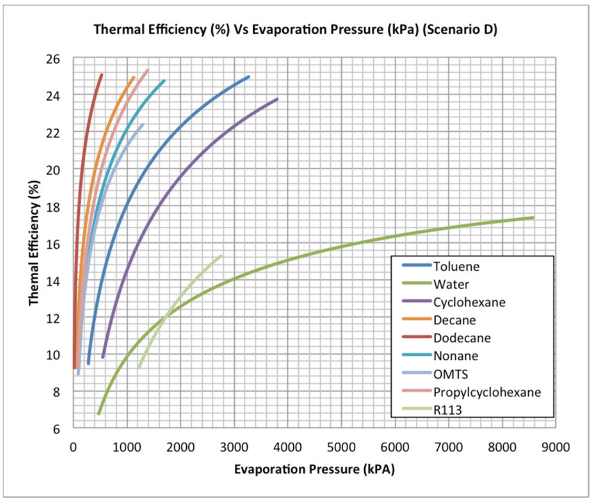
(i) Scenario A



(ii) Scenario B



(iii) Scenario C



(iv) Scenario D

Figure 7: Graph Thermal Efficiency (%) Vs Evaporation Pressure (kPa) for (i) Scenario A, (ii) Scenario B, (iii) Scenario C, and (iv) Scenario D

As in Scenario D, it is found similar pattern to Scenario C where almost organic fluids exceed water's thermal performance in much lower evaporating pressure. Suprisingly, R113 also performs better than water when it is operated more than 1.8MPa. As stated earlier, Propylcyclohexane produces highest thermal efficiency(25.30%) at 300ºC evaporating temperature and 1385.84kPa for this type of ORC system. Second followed by Dodecane where it gives thermal efficiency(η_{th}=25.06%) at 300ºC evaporating temperature and at only one-half(527.74kPa) of Propylcyclohexane's pressure. The difference of thermal performance between those 2 organic fluids is only 0.24% in spite of it takes about twice of evaporating pressure.

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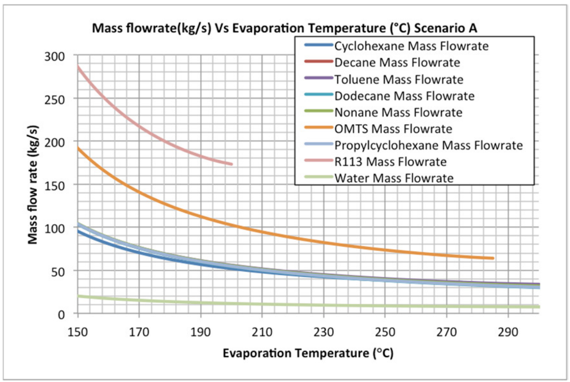
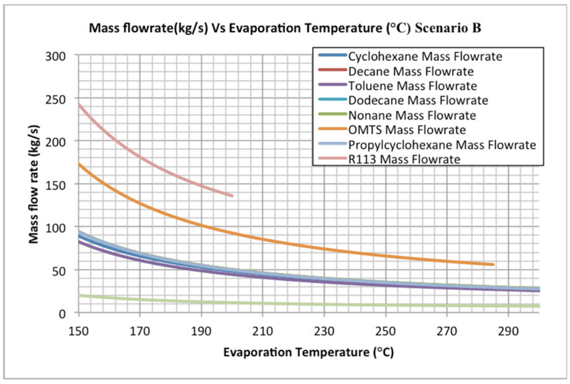
3.3 Mass Flow Rate vs Evaporation Temperature

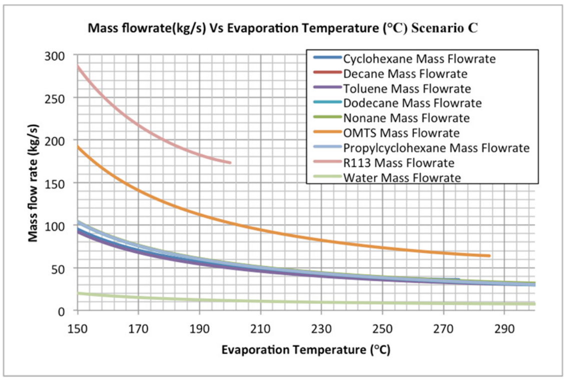
Figure 8 shows the graph of Mass Flow rate(kg/s) versus Evaporation Temperature (^{o}C) for Scenario A,B,C and D. The mass flow rate value is obtained directly from net output ((h5-h_6)-(h_1-h_2)) related to the electrical power output of 3MWe. All of the working fluids show similar downtrend line respect to the evaporation temperature. Higher evaporating temperature results lower value of mass flow rate.

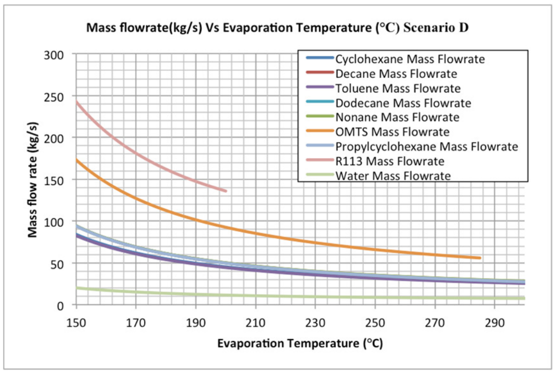




(i) Scenario A

(ii) Scenario B





(iii) Scenario C

(iv) Scenario D

Figure 8: Mass Flow Rate (kg/s) Vs Evaporation Temperature (^{o}C) for (i) Scenario A, (ii) Scenario B, (iii) Scenario C, and (iv) Scenario D

R113 shows highest mass flow rate compared to others, whereas using water as working fluid need the least mass flow rate. In the Rankine system, lower mass flow rate means better. This is because the size of pipeline and the scale size of the system also depending on the mass flow rate. The mass flow rate also affect the capital cost as higher mass flow rate means more sophisticated and material(due to higher mass of pipe) to support the pipeline and system

In all scenarios, organic fluids need higher mass flow rate compared to the mass flow rate of water (steam). It is even higher for R113 and OMTS, which need about 18 times and 7 times mass flow rate more than water's mass flow rate respectively. For the other 6 organic fluids, the mass flow rates are 3-4 times more than water, depending on the type of organic fluid. In

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ISSN (online): 2462-1943 I Vol. 4, No.1. Pages 29-46, 2016

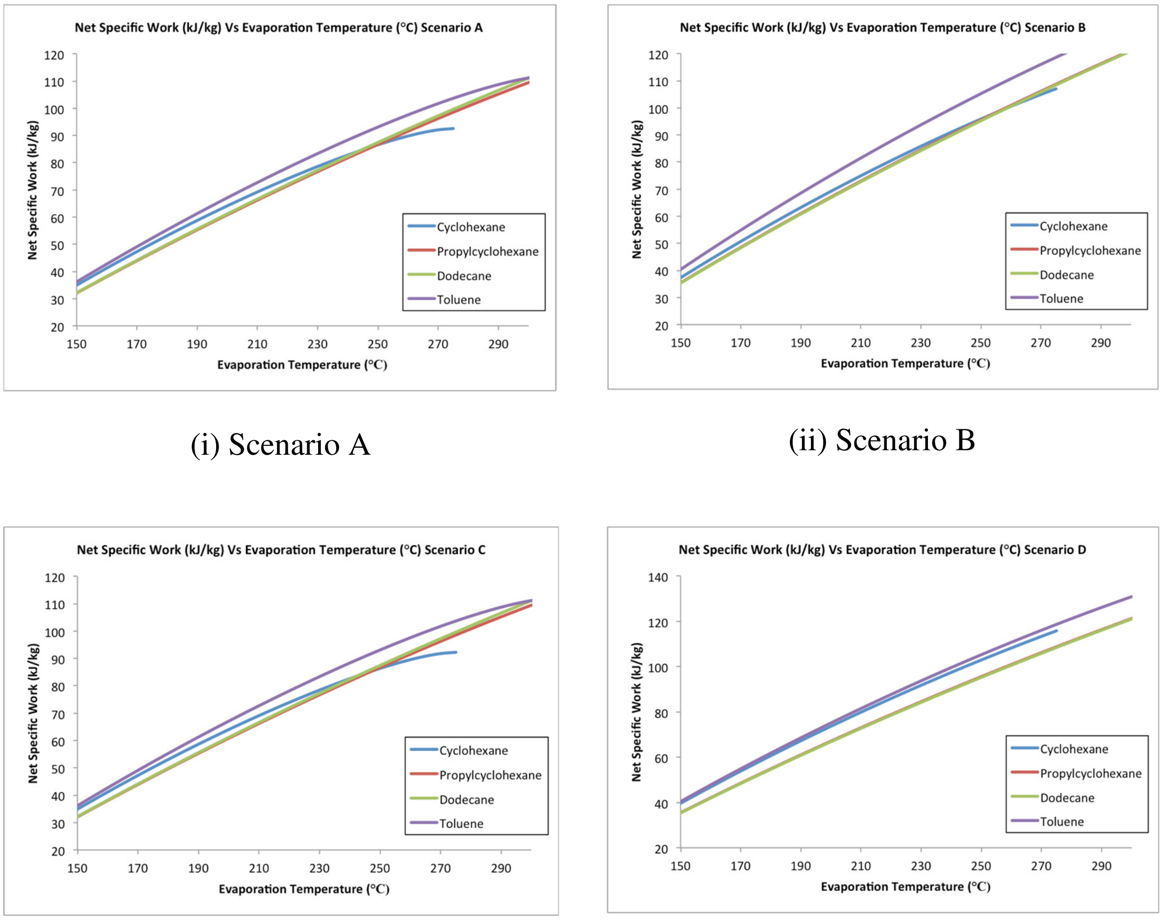
comparison of those 4 scenarios, the mass flow rate for each organic fluid in Scenario A is the same as in Scenario C, whereas mass flow rate in Scenario B is similar to Scenario D. This is because the saturated vapor is used at turbine's inlet for Scenario A and C but superheated is used at turbine's inlet for Scenario B and D. There is also a difference of mass flow rate between the systems using saturated vapor and superheated vapor. As shown in Table 1, mass flow rate needed in system with superheated vapor much lesser than the system of saturated vapor. In this case, superheated is necessary if to reduce the mass flow rate, and also obvious giving performance enhancement in system with IHE but not appropriate for simple system without IHE because it will reduce thermal performance.

Table 1: Summary of mass flow rate for every working fluid in each scenario.

Working Fluid	T_{eva} (°C)	P_{eva} (kPa)	Mass Flow rate for Scenario A (kg/s)	Mass Flow rate for Scenario B (kg/s)	Mass Flow rate for Scenario C (kg/s)	Mass Flow rate for Scenario D (kg/s)
Cyclohexane	275	3797.43	36.02	28.78	36.02	28.78
Decane	300	1123.94	30.89	27.84	30.89	27.84
Toluene	300	3269.50	33.73	25.47	33.73	25.47
Dodecane	300	527.74	30.00	27.47	30.00	27.47
Nonane	300	1689.13	31.89	28.16	31.89	28.16
Propylcyclohexane	300	1385.84	30.46	27.50	30.46	27.50
OMTS	285	1291.62	64.04	55.89	64.04	55.89
R113	200	2749.53	173.18	135.872	173.18	135.872
Water	300	8569.77	N/A	7.52	N/A	N/A

3.4 Net Specific Work vs Evaporation Temperature

Figure 9 visualizes the Net Specific Work (kJ/kg) Vs Evaporation Temperature (°C) in all types of scenarios. As presented before, the mass flow rate of organic fluids is directly related to net specific work ($P_{turbine} - P_{pump}$) to get the desired output, which is in this study is 3MWe. In all figures above, it is obvious Toluene has highest net specific work compared to other top 3 organic fluids which are Propylcyclohexane, Dodecane and Cyclohexane. In all scenarios, Dodecane is the second best in term of net specific work($(h_5-h_6)-(h_1-h_2)$)at its optimal evaporation temperature(300°C for biomass application). Cyclohexane has much higher specific work than Dodecane and Propylcyclohexane in its operating temperature range, but limited at only 275°C.



(i) Scenario A

(ii) Scenario B

(iii) Scenario C

(iv) Scenario D

Figure 9: Net Specific Work (kJ/kg) Vs Evaporation Temperature (oC) for (i) Scenario A, (ii) Scenario B, (iii) Scenario C, and (iv) Scenario D

3.5 Biomass Heat Sources

Figure 10 illustrates the relation between all 6 organic fluids in 4 scenarios. Organic fluid R113 and OMTS and also configuration of Scenario B are excluded in this graph analysis. Based on the figure 4.25, heat sources needed from biomass sources are more than 20MW for Scenario A, and 13-15MW for Scenario C and D. For scenario A, the least heat source is needed if ORC uses Toluene (20.86MW) as working fluid, for Scenario C is Dodecane (14.03MW) and for Scenario D is Propylcyclohexane (13.17MW). There is not much difference for Scenario C and D. This difference is one of main economic factors in order to decide ORC with IHE should be overheat to superheated state or not. This heat sources are directly proportional to the thermal efficiency of the system. The higher thermal efficiency, the lower biomass heat source is needed. This relation is also directly related to the amount of biomass to be burnt. The amount of biomass needed is also depending on the calorific content value of biomass itself. As review in previous section, usually the Low Heating Value (LHV) is used in obtaining the heating value of biomass combustion, hence the fuel price, amount of biomass and other economic analysis can be done further.

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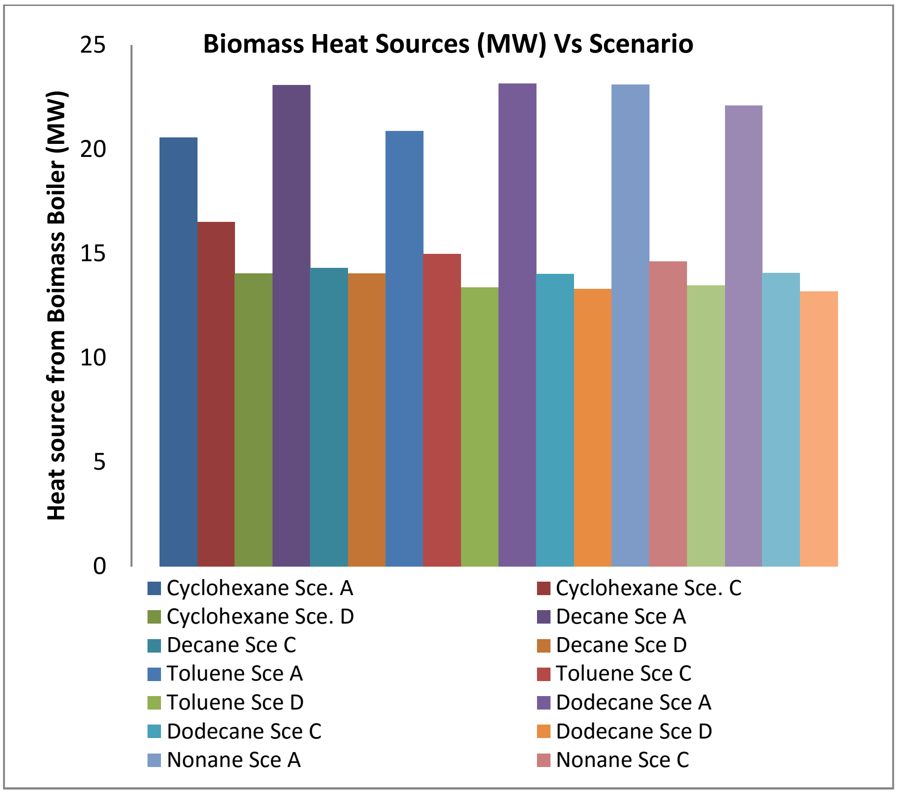
ISSN (online): 2462-1943 I Vol. 4, No.1. Pages 29-46, 2016



Remark: Sce A: Scenario A, Sce C: Scenario C, Sce D: Scenario D

Figure 10: Biomass Heat Sources in all scenarios.

4.0 CONCLUSION

This paper presents the performance of Organic Rankine Cycle system in biomass application in producing a 3MWe output. The study is done by focusing on selection of organic fluid as ORC's working fluid. The main parameter or objective function in this study is to obtain the highest thermal efficiency of the system. Nine fluids have been investigated, 8 of them are organic fluids and the other one is conventional water.

In all 4 scenarios, the highest thermal efficiency is found in Scenario D. The second best is Scenario C, followed by Scenario A and the most ineffective is Scenario B. In Scenario A and B, Toluene gives the highest thermal efficiency. Dodecane is the best performer in Scenario C and Propylcyclohexane edges other organic fluids in Scenario D. Generally, water is ineffective in all scenarios in range of 150°C to 300°C. To choose the best configurations of ORC for this study, Scenario D is not directly selected because its improvement only a few percent higher than Scenario D, meanwhile its system has to be more complicated and need higher cost. As discussed in previous section, Scenario C is more appropriable because of its simpler system than Scenario D and gives huge improvement than Scenario A.

With addition of IHE (Scenario C), performance of ORC can be improved by 83% compared to the performance in Scenario A (without IHE). In terms of thermal efficiency(η_{th}), the highest value obtained in Scenario C is 23.76% that is by using Dodecane as working fluid. The

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ISSN (online): 2462-1943 I Vol. 4, No.1. Pages 29-46, 2016

improvement by IHE addition varies from one type of organic fluid to another. As briefly discussed in previous section, the magnitude of IHE impact is depending on the slope of organic fluid in *T*-*s* diagram.

Even though almost organic fluids in this study outperform water in term of thermal efficiency, their mass flow rates (kg/s) are always higher than water in all cases. It means,ORC needs bigger feed pump than steam plant in all cases. The simulation results in this study are done for subcritical condition, which is low than critical pressure of the organic fluid. Then, it is recommended to continue the studies with supercritical condition (at point of critical pressure) in order to study its effects on the system.

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