EFFECT OF ORGANIC RANKINE CYCLE MODIFICATION TO SYSTEM PERFORMANCE

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ABSTRACT

The Organic Rankine Cycle (ORC) is the most used power plant type in the world. The performance of this type of power plant is investigated as an alternative of means to produce electricity. Specifically, three subtype of ORC system are investigated: a simple ORC system, an ORC system with a recuperator, and a regenerative ORC system with open feedwater.

The brine data is based on the brine from Jailolo geothermal field located in West Halmahera, Indonesia. Previous exploration studies identified the field as two-phase water-dominated reservoir with a brine enthalpy of around 1100 kJ/kg and steam fraction of 20%. It is planned to inject the brine at a minimum temperature of 90°C.

Specifically, the effect of modification of usage on the performance of an ORC system, without changing the turbine inlet pressure is investigated in this study. It is found that modifying the system will improve the thermal efficiency and brine output temperature, especially in a regenerative ORC system. This improvement is offset by the increased demand for brine from the reservoir. It is also found that in this scenario the exergy efficiency increases if a recuperator is used but is reduced if a regenerative ORC system is used.

1. INTRODUCTION

A binary-based geothermal power plant is the most commonly installed type of power plant. From a recent report by Eliasson (2011) it is known that 44% of geothermal power generating units in the world are binary systems, especially the Organic Rankine Cycle (ORC) system.

Jailolo geothermal field has a water-dominated reservoir with a medium temperature of 179°C. This temperature means ORC based power plant is suitable for use in this field. This ultimate goal of this study is to find the optimal power plant configuration to be used in this field.

In this paper, the results of the first three parts of the study are reported. Those parts are:

1) Initial potential working fluid working fluid
2) Optimal simple ORC inlet pressure calculation
3) Study of the effect of ORC system modification

2. ORC DESIGN AND CALCULATION DETAIL

In this study, three types of ORC system are considered: a Regular ORC system, an ORC system with a recuperator, and a Regenerative ORC system with open feedwater (referred to simply as a Regenerative ORC system hereafter). The schematics for these ORC systems are shown in Figure 1.

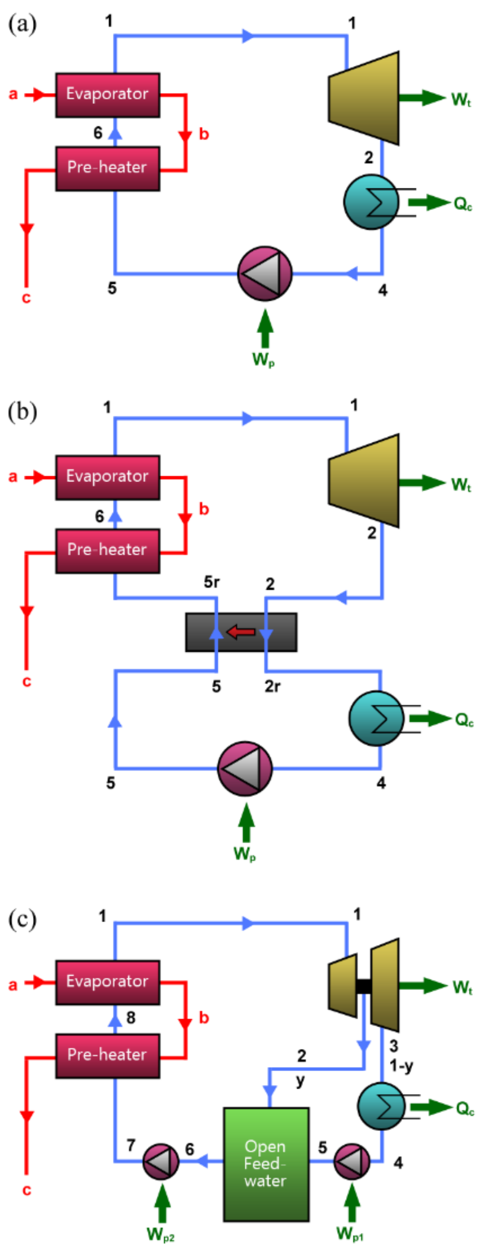

Figure 1: Organic Rankine Cycle configurations: (a) Regular ORC system (b) ORC system with recuperator (c) Regenerative ORC system with open feedwater.

To study the performance of these ORC systems thermodynamics analyses must be carried out. In this study, the calculation for a Regular ORC and an ORC with a recuperator is based on the method described by DiPippo (2008), while the Regenerative ORC calculation used is based by the description by Moran (2006). In the following section the steps of these calculations will be explained briefly.

2.1 Regular ORC system

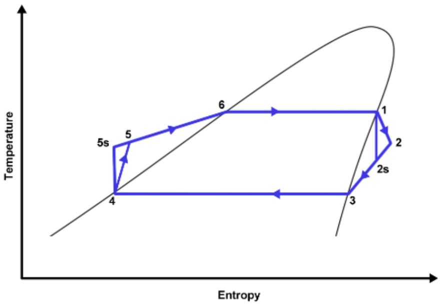

Figure 2: Temperature-entropy diagram for a Regular ORC System.

To analyze the regular ORC system, consider the Temperature-Entropy diagram in Figure 2 above. The net electricity produced by the system is related to the amount of work produced in the turbine and the amount of work used by the pump. It can be calculated with the equation below:

$$\dot{W}_{turb} = \eta_t \cdot \dot{m}_{wf} \cdot (h_1 - h_{2s})$$

$$= \dot{m}_{wf} \cdot (h_1 - h_2)$$

$$\dot{W}_{pump} = {}^{1}/_{\eta_p} \cdot \dot{m}_{wf} \cdot (h_{5s} - h_4)$$

$$= \dot{m}_{wf}(h_5 - h_4)$$

$$\dot{W}_{net} = \dot{W}_{turb} - \dot{W}_{pump}$$

The total heat entering to the system is defined as:

$$\dot{Q}_{in} = \dot{m}_{wf} \cdot (h_5 - h_6)$$

With these two parameter known the system thermal efficiency can be calculated:

$$\eta_t = \frac{\dot{W}_{net}}{\dot{Q}_{in}}$$

The thermal efficiency equation above will be used for all the systems studied. Thus, the systems can be compared to each other.

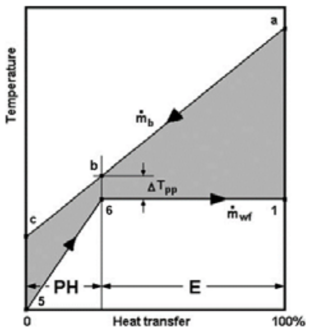

Figure 3: Temperature-entropy diagram for a Regular ORC System. (DiPippo, 2008)

Figure 3 is used for calculation of the brine output temperature and the amount of brine needed. To calculate the brine output temperature, the term pinch-point temperature difference (here forward referred to as the pinch-point) is introduced. This term relates to the temperature difference between the working fluid temperature for the high-working pressure (state 6 in the picture) and the brine temperature when leaving evaporator (state b in the picture).

$$\Delta T_{pp} = T_b - T_6$$

To learn about the quality of energy used by the system, the exergy efficiency is studied. For a regular ORC system, the usable energy is defined as the net work of the system, while the total exergy available is defined as the exergy that is released from the brine.

$$\dot{E}_{in} = \dot{m}_b \cdot (e_a - e_c)$$

Mathematically, the exergy efficiency for a regular ORC system is defined as:

$$\eta_{ex} = \frac{\dot{W}_{net}}{\dot{E}_{in}}$$

2.2 ORC system with a recuperator

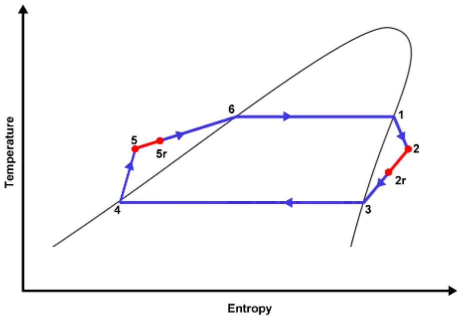

Figure 4: Temperature-entropy diagram for ORC system with a Recuperator

A recuperator is a heat exchanger that uses waste heat to heat the working fluid before it enters the pre-heater/evaporator. In this study the performance of a recuperator is defined as the recuperator temperature difference. Thus this term denotes the difference in the low-pressure working fluid before and after passing through the recuperator.

$$\Delta T_r = T_2 - T_{2r}$$

By knowing the temperature in state 2r, the temperature in state 5r can be determined by:

$$h_{5r} = h_5 + (h_2 - h_{2r})$$

Note that in the calculation of net work, the states 2 and 5 present in a regular ORC system equations must be replaced by their recuperator-corrected states, which are states 2r and 5r respectively.

The usage of waste heat will increase the system exergy efficiency. Therefore, the exergy efficiency equation must be corrected. In this case, the exergy efficiency is defined as:

$$\eta_{ex-rec} = \frac{\dot{W}_{net} + \dot{Q}_{rec}}{\dot{E}_{in}}$$

$$\dot{Q}_{rec} = \dot{m}_{wf} \cdot (h_2 - h_{2r})$$

2.2 Regenerative ORC system

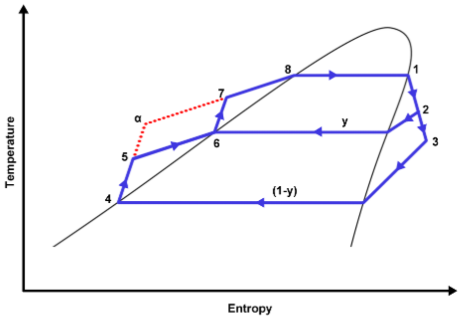

Figure 5: Temperature-entropy diagram for a Regenerative ORC system with Open Feedwater

Unlike the systems described above, a regenerative ORC system work in two stages and at three working pressures. The intermediate pressure is often referred as the bleed pressure. When the turbine reaches this pressure, a fraction of the working fluid will be bled to open feedwater, while the rest of it will enter the second-stage turbine to generate further work. The amount of working fluid leaving the turbine relative to the total working fluid used in the system is defined as *y* and can be calculated mathematically by:

$$y = \frac{h_6 - h_5}{h_2 - h_5}$$

As mentioned before, the system works in two stages. That means to determine the total performance of the system, the contribution of each stage must be calculated. In this case, the specific work of each system component is:

$$\dot{w}_t = (h_1 - h_2) + (1 - y) \cdot (h_2 - h_3)$$

$$\dot{w}_p = (h_7 - h_6) + (1 - y) \cdot (h_5 - h_4)$$

By inspecting the diagram, the amount of heat entering the system can be calculated as:

$$\dot{Q}_{in} = \dot{m}_{wf} \cdot (h_1 - h_7)$$

The efficiency equation, on the other hand, follows the regular ORC system calculation.

3. BASE PARAMETER IDENTIFICATION

Before the calculations above can be conducted, the base parameters related to the system in question must be identified. The parameters are divided to two main categories: environmental parameters and design parameters.

The environmental parameters are related to the geothermal system in question. From the feasibility study done by AECOM, it is known that Jailolo geothermal field is two-phase water-dominated reservoir with brine enthalpy of around 1100 kJ/kg and steam fraction of 20%. This corresponds to fluid temperature of 179°C. The dead state conditions are set to common values used, which are 25°C and 0.1 MPa.

At this stage, it is planned to develop two 5 MWe power plants at Jailolo geothermal field. The proposed design parameters for the ORC system plan in Jailolo are shown in Table 1. The condensation temperature is set so that the calculation results become more reliable and can be implemented in the field.

Table 1: Design Parameters of the ORC system investigated in this study

Parameter	Notation	Value	Unit
Net work	$\dot{W}_{net}$	5000	kW
Condensation temperature	T_3	45	°C
Turbine Efficiency	η_t	90	%
Pump Efficiency	η_p	80	%
Pinch-point Temp. Difference	ΔT_{pp}	5	°C
Recuperator Temp. Difference	ΔT_r	10	°C

4. POTENTIAL WORKING FLUID SELECTION

4.1. Initial calculation

Before system optimization could be conducted, a suitable list of potential working fluids must be obtained. These potential working fluids are selected from a list of 104 pure working fluids whose data are provided by NIST REFPROP 9.0. A certain working fluid can be said to have potential if, for an arbitrary pressure, its usage makes the brine output temperature reach at least 90°C.

From 104 working fluid studied, 18 working fluids were found to be suitable as a working fluid. Those working fluids are:

Acetone, Benzene, Cis-butene, Ethanol, Heptane, Hexane, Isopentane, Methanol, MM, Pentane, R11, R113, R123, R141b, R21, R234ca, R245mfc, Sulful Dioxide

Furthermore, there are two working fluids that almost passed the criteria, namely: Neopentane and Trans-butene. Another two working fluids, Butane and R245fa, can only be used if the pinch-point value is reduced. At this stage of the study, these working fluids are ignored but might be used if the findings make the usage of them feasible.

4.2. Regular ORC system optimization

The system inlet turbine pressure for every working fluid must be optimized so they can be compared one to another. For this calculation, the turbine pressure is optimized so that the maximum thermal efficiency is reached.

The pressure optimization results for the nine best potential working fluids are shown at Table 2. It can be observed that the performance is limited by the brine output temperature criterion that was set before. It can also be seen that there is a correlation between system efficiency and the amount of brine needed.

Another interesting thing to note is that for the same base parameters, hydrocarbon-based working fluids (Cis-butene, Isopentane, Pentane, and Hexane) need a far smaller amount of working fluid compared with refrigerant-based working fluids.

5. EFFECTS OF ORC SYSTEM MODIFICATION

To learn about the effects of ORC system modification, the variation of parameters must be minimized. For this purpose, the optimized inlet turbine pressure as shown in Table 2 is used for current stage of the study. In this section the qualitative performance will be examined, while a numerical comparison will be discussed in the next section.

Table 2: Regular ORC system optimization calculation result

Working Fluid	P_{high} (MPa)	η_t (%)	η_{ex} (%)	T_c (°C)	$\dot{m}_b/MW$ (kg/s.MW)	$\dot{m}_{wf}/MW$ (kg/s.MW)
Cis-butene	2.42	14.55%	25.68%	90.00	17.82	15.37
R245ca	1.79	14.46%	25.53%	90.00	17.92	27.69
Isopentane	1.25	14.06%	24.80%	90.00	18.44	15.65
R123	1.25	14.07%	24.79%	90.00	18.45	34.87
R365mfc	1.11	14.03%	24.76%	90.00	18.48	27.46
Pentane	0.99	13.95%	24.59%	90.00	18.60	15.13
R113	0.67	13.72%	24.16%	90.00	18.93	38.48
Hexane	0.40	13.61%	23.98%	90.00	19.08	15.29
R141b	0.92	13.60%	23.93%	90.00	19.11	28.16

5.1. ORC System with recuperator

To qualitatively learn about recuperator performance, a Recuperator feasibility chart was created. This chart was created by plotting inlet turbine pressure on the x-axis and two parameters on the y-axis, namely: brine output temperature and exergy destroyed inside the recuperator. Both y-axes are connected by a horizontal line at the minimum value for each parameter (in this case 90°C and zero respectively). A working fluid is said feasible for a certain inlet turbine pressure if both parameters are above the limit line.

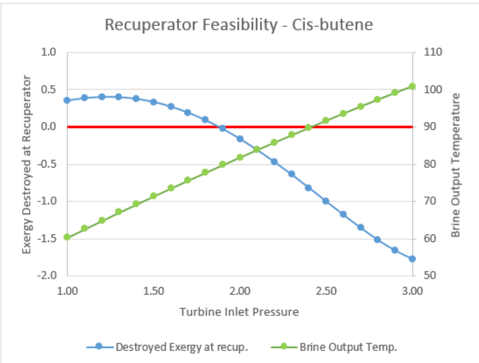

Figure 6: Recuperator feasibility chart for Cis-butene

It is found that of the 9 potential working fluid candidates, only Cis-butane cannot be used at all. If its chart, as shown by Figure 6a, is inspected, it can be seen that when the inlet turbine pressure is below ~1.75 MPa, the recuperator can still work thermodynamically but cannot meet a brine temperature release above 90°C. On the other hand, if the inlet turbine pressure is above ~1.75 MPa, the exergy destroyed inside recuperator is negative. Therefore it cannot work thermodynamically.

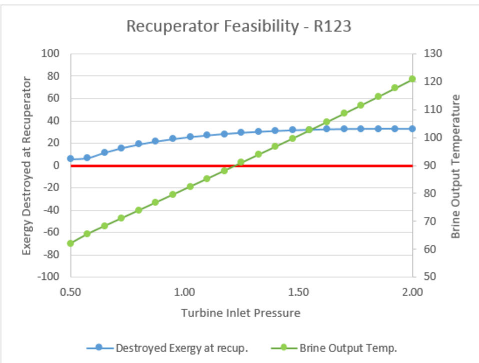

Figure 7: Recuperator feasibility chart for R123

Other working fluid candidates show a similar trend. The chart for R123 is used as example for this discussion. If Figure 6b is inspected, it can be deduced that the system can work thermodynamically as the exergy destroyed inside the recuperator is positive, but the design is limited by the minimum brine output temperature.

5.2. Regenerative ORC system

In a regenerative ORC system there are two parameters that can be modified, namely: inlet turbine pressure and extraction pressure. As the inlet turbine pressure was set constant at this point, only the extraction pressure could be modified. The extraction pressure was varied between the inlet turbine pressure and condensation pressure.

There are multiple possible optimization targets that could be selected by varying the extraction pressure. To select the correct target, the effect of varying the extraction pressure on those targets is studied. The target parameters studied are: brine output temperature, the amount of brine needed, thermal efficiency and exergy efficiency.

Qualitatively, every working fluid exhibits the same behaviour on these target parameters. Therefore, one working fluid, Isopentane, is selected as representative.

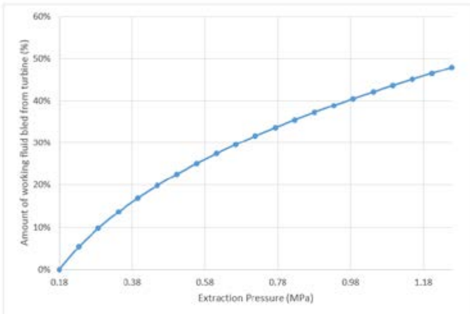

Figure 8: Extraction pressure vs amount of working fluid bled for Isopentane.

The effect of extraction pressure change on the amount of working fluid bled from the first turbine is shown in Figure 8. It can be seen that increasing extraction pressure will generally increase the amount of working fluid bled. At a higher extraction pressure, the heat needed by the working fluid that come out from the turbine (state 5 at Figure 5) to reach saturation point at the extraction pressure (state 6 at Figure 5) increases. This causes the aforementioned phenomenon.

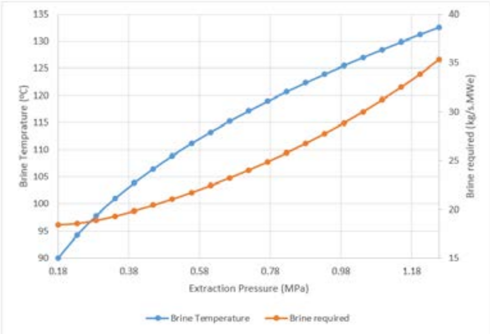

Figure 9: Extraction pressure vs brine parameters for Isopentane.

The effects of extraction pressure change on brine parameters are shown in Figure 9. It can be seen that brine parameters generally rise along with the increasing extraction pressure. When extraction pressure is raised, the amount of heat extracted from the brine is reduced. This leads to the rise of brine output temperature. As the amount of electricity produced is the same, the reduction of heat extracted means more brine is needed.

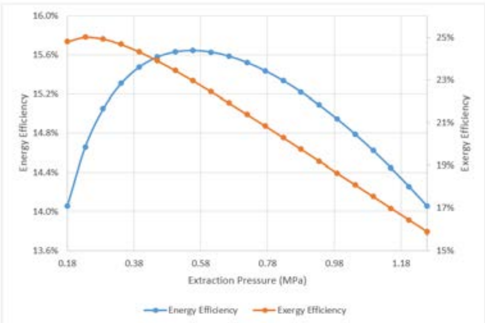

Figure 10: Extraction pressure vs system efficiency for Isopentane.

The effect of extraction pressure change on system efficiency is shown in Figure 10. It can be seen that the maximum thermal efficiency is reached when the extraction pressure is around 35% of the difference between the two working pressures. As shown by Figure 8, the amount of working fluid bled is large when the extraction pressure is high. This will reduce the specific work generated and reduce the thermal efficiency. On the other hand, the specific heat extracted by the working fluid is larger when the extraction pressure is low. Below the optimum point, the increase in rate of heat extracted is larger than the increase in rate of specific work generated. This, in turn, will reduce the thermal efficiency.

The maximum exergy efficiency reached when the extraction pressure is near the condensation pressure. That is, when the working fluid is barely being bled. Inefficiency in the system is caused by the larger amount of working fluid needed for the same amount of work generated.

After looking at these target parameters, it was decided to optimize the extraction pressure to maximise thermal efficiency. This parameter was selected so that the effects of performance modification could be more clearly demonstrated.

6. COMPARISON OF ORC SYSTEM MODIFICATION

6.1. Thermal efficiency

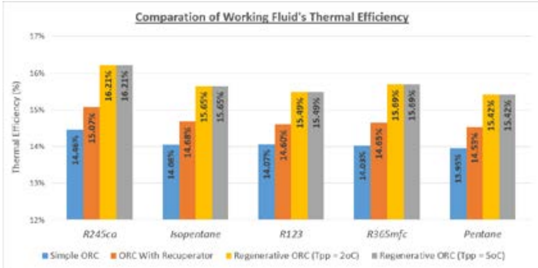

Figure 11: Comparison of thermal efficiency for several of the best working fluid candidates

The thermal efficiency generally increased with the usage of a modified ORC system. The installation of a recuperator will increased the thermal efficiency by ~4%. The usage of a Regenerative ORC gives higher increase of thermal efficiency compared to that for a ORC system with a recuperator. For an optimum extraction pressure, a regenerative ORC system increases the efficiency by ~10-12%. The thermal efficiency is an internal parameter of an ORC system, and therefore a shift in the pinch-point will not change it.

6.2. Exergy efficiency

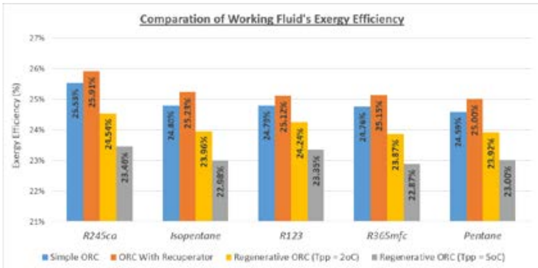

Figure 12: Comparison of exergy efficiency for several of the best working fluid candidates

The goal of a recuperator is to use the heat released by a regular ORC system. Hence, it is clear that the installation of a recuperator will increase the system exergy efficiency. For the configuration used in this study, recuperator usage increased exergy efficiency by up to 1.5%.

On the other hand, a regenerative ORC reduce the efficiency significantly. The average drop for the same pinch-point value is 7%. To reduce this drop, the exergy efficiency for a smaller pinch-point value was observed. Unfortunately for this case the exergy efficiency could not be made better than the value for a simple ORC system. The average difference for these to configuration is about ±3%.

6.3. Specific working fluid needed

The amount of working fluid needed is affected by the characteristics of the working fluid used. The effects of fluid characteristics were not observed in this study. Even so, it is shown that generally the working fluids exhibit similar behaviour.

A regular ORC system and an ORC system with a recuperator work on the same operation pressure. It follows that the amount of fluid needed to produce the same amount of electricity will be the same as well.

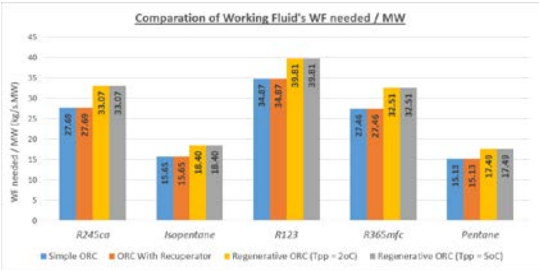

Figure 13: Comparison of specific amount of working fluid needed for several of the best working fluid candidates

For a regenerative ORC system, the amount of working fluid needed is highly dependent on the extraction pressure used. At the optimum value the amount of working fluid needed will increase by around 14%-20%.

From the discussion of energy efficiency above, it is implied that a pinch-point change will not shift the optimum value of extraction pressure. Therefore, the amount of working fluid needed will not change regardless of the pinch-point value.

6.4. Specific brine needed

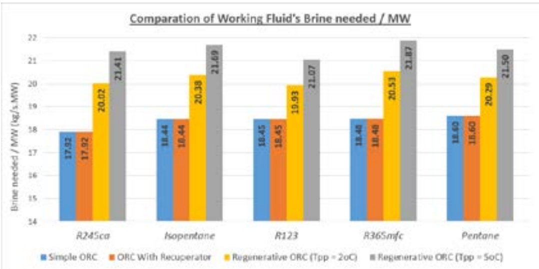

Figure 14: Comparison of specific amount of brine needed for several of the best working fluid candidates

The amount of brine needed in an ORC system is affected by three parameters: working pressure, the amount of working fluid used, and the pinch-point value selected. In this comparison, these three parameters in a regular ORC system and an ORC system with recuperator are the same. Therefore, the amount of brine needed is also the same. The amount of working fluid needed in a regenerative ORC system is larger. This correlate to the increased amount of brine needed.

In a regenerative ORC system, the increase of working fluid needed is equal to the increase of brine needed if the pinch-point value is not changed (14%-20%). If the pinch-point value is decreased, the system will take more heat from the brine. This causes a reduction in the amount of the brine needed. For the pinch-point value of 2^{o}C, the brine needed is increased by 8%-12% compared to the amount used in a regular ORC system.

6.5. Brine output temperature

Optimization result of regular ORC system make the output temperature of the system equal to the minimum output temperature, that is, 90°C. The usage of a recuperator reduces the amount of heat extracted from brine at the pre-heater. The amount of heat reduction is minor, and hence the increase in temperature is small. The average temperature increased for 3.5°C.

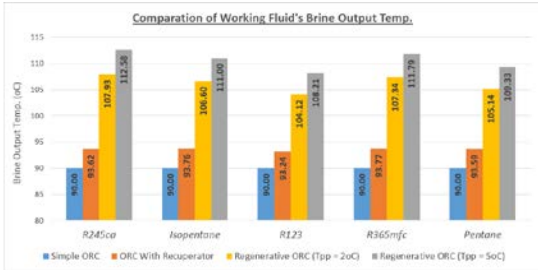

Figure 15: Comparison of brine output temperature for several of the best working fluid candidates

Regenerative ORC can reduce the heat needed significantly if compared to an ORC system with a recuperator. For the same value of pinch-point, the increase of brine temperature averaged 20°C. If the pinch-point is reduced, the brine output temperature is dropped due to an increased heat usage from brine. In this study, the average temperature increase is 16°C if compared to a regular ORC system.

This significant increase in temperature makes feasible the usage of four working fluids that were not included before (Neopentane, Trans-butene, Butane, and R245fa). These four working fluids will be included in the next stage of the study of a regenerative ORC system.

7. FUTURE WORKS

After this study, it is planned to optimize the modified system even further. In this way, a thermodynamically optimal system for Jailolo geothermal field can be chosen. It is also planned to do an economic analysis of suggested power plant configuration. Ultimately, the research end result will produce recommendation to the developer for further development of the field.

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