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Design and manufacturing of organic rankine cycle (orc) system using working fluid r-134a with helical evaporator and condenser

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Abstract. Waste heat from industries such as steam power plants can be utilized to meet the world's electricity need. However, it cannot be converted efficiently to electric power by using conventional power generation methods as opposed to a technology called Organic Rankine Cycle (ORC). ORC is one of the power plant systems that is a modification of the Rankine Cycle using organic working fluid. In this research, ORC was designed and manufactured using R-134a as working fluid and helical heat exchanger as evaporator and condenser. The design of ORC systems based on simulation using Cycle Tempo 5.0 with evaporator temperature of 90°C, condenser temperature of 10°C, inlet pressure of pump of 0.55 MPa, and inlet pressure of turbine of 0.79 MPa. The results of this study showed the length of tube evaporator and condenser of 10.61 m and 10.56 m, respectively, with system efficiency achieved at 3.8%. Based on experiment, with evaporator temperature of 95°C, condenser temperature of 10°C, inlet pressure of pump of 0.48 MPa and inlet pressure of turbine of 0.52 MPa so resulted of system efficiency of 3.33%.

1. Introduction

Indonesia is one of the countries that has great geothermal resources potential, but a lot of the natural resources has been used to meet energy needs [1]. Human needs for energy will increase because of the high population growth, economic growth, industrial expansion and the advancement of technology used by humans [2]. It causes less energy on earth. Worldwide energy consumption has increased by more than 40% over the last few decades and causes significant environmental problems and economic value. The misused energy from fuel derived from engine exhaust is more than 30-40% and only about 12-25% can be converted for useful work [3].

Generally, energy and non-renewable energy sources. The fulfillment of energy needs so far has been focused on usage of non-renewable or fossil energy sources, such as petroleum, coal and natural gas which are currently in critical condition with limited reserves and were known had a negative effects on the environment such as the global warming potential, ozone depleting potential and acid rain [4][5]. Therefore, needed an effort to found alternative energy sources that can divert energy consumption from fossil energy which is more efficient and friendly to the environment [6].

Utilization of renewable energy sources such as wind energy, biomass, geothermal and waste heat is a way to solve the problems. In recent years, intensive research has been done on technology that can be converting for low temperature and low-pressure to produce energy. The heat source can be obtained from various thermal processes, one of them is a waste heat recovery [7].

Waste heat recovery from industries such as steam power plants has the potential to reduce dependence on fossil energy and to meet the needs of electricity in the world. However, the low temperature of the source could not be converted efficiently into electricity when using conventional power generation methods, so in this study, the heat converting technology can be realized in an Organic Rankine Cycle system [8][9].

Organic Rankine Cycle (ORC) was accepted as a technology to converting low-temperature to electrical power to ease the operation, low maintenance, and good operating pressure. The vapor



produced by the working fluid could be used to drive the turbine [10]. Generally, grade of the temperature is classified by temperature range, there are three classifications of it, such as high temperature ($>650^{\circ}\text{C}$), medium temperature ($230\text{--}650^{\circ}\text{C}$) and low-temperature ($<230^{\circ}\text{C}$) [10]. Thus, the ORC system will be operated under the 230°C temperature.

Organic Rankine Cycle (ORC) is one of the power generation systems that is a modification of Rankine Cycle using organic working fluid (refrigerant and Hydrocarbon) [11]. Organic Rankine Cycle (ORC) has four major components, they are evaporator, turbine, condenser, and pump. The working fluid is pumped into the evaporator to be heated to generate the steam, the vapor is used to drive the steam turbine, the turbine spin result will be used to drive the generator and generate the power source, the turbine expansion vapor is condensed and flowed by the pump back to the evaporator [1][12].

There are much varieties of organic working fluids, which has the advantages and disadvantages respectively. Classification of working fluid based on the thermodynamics, environmental and safety criteria also availability in research region [11][12].

With this study, it is hoped that it can be used as one of the references for advanced research or other research that want to design this ORC system to produce bigger electric energy capacity.

2. Energy Analysis of Rankine Cycle System

Figure 1a shows the schematic diagram of basic Rankine Cycle. In ORC, a boiler is replaced by heat exchanger or evaporator. In this study, heat exchanger that used is shell-and-tube evaporator and condenser with helical tube.

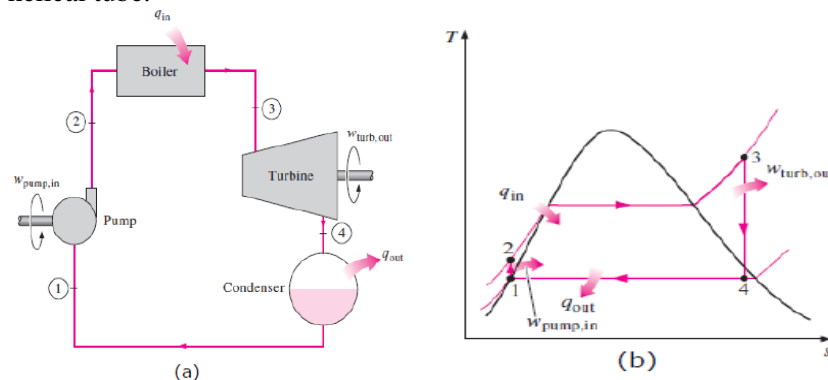


Figure 1. Schematic diagram of the Rankine Cycle (a); T-s diagram of ORC (b)

The ORC system diagram is shown in Figure 1b, the process of ORC starts from the fluid is pumped into the evaporator and occur the heat transfer process between fluid and hot water as the heater, the fluid will be changed to vapor condition, the steam will drive the turbine, with isentropic expansion that means the temperature and pressure will decrease, the fluid flows to the condenser, in the condenser the steam will be change to liquid condition because of the heat transfer process between fluid and cold water. Process of ORC is described as follow:

1. Process 1-2: Isentropic compression in a pump.
2. Process 2-3: heat addition in a evaporator.
3. Process 3-4: isentropic expansion in a turbine.
4. Process 4-1: heat rejection in a condenser

Energy analysis of the ORC will be describe as follow:

$$\eta_{th} = \frac{w_{net}}{q_{in}} = \frac{w_t - w_p}{q_{in}} = \frac{\dot{m}(h_3 - h_4) - (h_2 - h_1)}{\dot{m}(h_3 - h_2)} \quad (1)$$

3. Working Fluid Selection

The selection of working fluid is an important decision criteria for the performance and reliability of the design procedure of an Organic Rankine Cycle power plant. The characteristics of the selected Organic Rankine Cycle (ORC) working fluid must be compatible with thermodynamic characteristics, high temperatures stability, non-toxic, non-corrosive, appropriate pressure (evaporators and condensers) and their environmental impact (related to ODP and GWP) [11]–[13].

In general, working fluids are classified into three categories, namely wet fluids, isentropic fluids and dry fluids. The classification is based on the value of E which is the opposite of the slope of the steam saturation curve. The fluids having an $E > 0$ are classified as wet fluids. Fluid having $E < 0$ are classified as dry fluids. The fluid having the value $E \approx 0$ is classified as isentropic fluid [11]–[13].

$$E = \frac{c_p}{T_H} - \frac{\frac{nT_{rH} + 1}{1 - T_{rH}}}{T_H^2} \Delta H_{vap} \quad (2)$$

where:

E = ds/Dt

C_p = specific heat of the fluid at constant pressure (kJ/kg)

T_H = evaporation temperature of the fluid (°C)

n = 0.375 or 0.385

T_{rh} = decreased of evaporation temperature (°C)

ΔH_{vap} = latent heat (°C)

In addition, the classification of working fluids based on safety to the environment is as follows:

- | | |
|---|------------------------------|
| 1. Based on Ozone Depleting Potential (ODP) | 3. Based on ASHRAE Safety 34 |
| a. Medium, ODP < 0.1 | a. A, non-toxic |
| b. High, ODP > 0.1 | b. B, toxic |
| 2. Based on Global Warming Potential (GWP) | c. 1, not flammable |
| a. Low, GWP < 150 | d. 2, potentially flammable |
| b. Medium, GWP between 150 - 2500 | e. 3, flammable |
| c. High, GWP > 2500 | f. L, flammable |

Based on Karmalis [11], we classified 10 candidate working fluids that would choose to use in this study as shown in table 1. This classification based on the thermodynamical criteria of working fluid.

Table 1. Thermodynamics Criteria

ASHRAE code	Tcr (° C)	Pcr (MPa)	Type of fluid
R123	183,381	3,6618	Dry
R124	122,245	3,6242	Wet
R134a	101,21	4,059	Isentropic
R152a	113,41	4,516	Wet
R21	178,48	5,181	Wet
R227ea	101,76	2,926	Wet
R245fa	154,2	3,64	Dry
R290	96,825	4,2476	Isentropic
R32	78,25	5,782	Wet
R600	152,125	3,796	Dry

Classification based on the characteristics of the working fluid that was described in Quoilin [12], such as:

1. Efficiency of output power should be higher than heat source.
2. Working fluid inlet turbine in positive or isentropic saturation vapor curve.
3. High environmental safety, it means value of ODP, GWP, the toxicity, and the flammability should be as low as possible
4. Good availability and low cost.

Based on the type of fluid, working fluid of R123, R134a, R245fa, R290, and R600 can be used in Organic Rankine Cycle system because they had positive and infinitive vapor saturation curve. In addition, working fluid based on environmental and safety criteria classifications shown in Table 2:

Table 2. Environmental and Safety Criteria

ASHRAE code	ODP	GWP	Safety
R123	0,02	77	B1
R124	0,022	609	A1
R134a	0,055	1430	A1
R152a	0	124	A2
R21	0,04	151	B1
R227ea	0	2900	B1
R245fa	0	1030	B1
R290	0	3,3	A3
R32	0	675	A2L
R600	0	4	A3

From the table above, R290 and R600 has a low value of ODP and GWP, however they had high environmental impact. From the safety criteria, R-134a and R124 can be used in ORC system. We have been selected 1 of 10 working fluid and selected the working fluid is R-134a, cause of availability in market.

4. Methodology

In this study, we used the method of design and manufacturing that performed for the design, manufacture, and experiment of the ORC systems. The schematic of systems described in Figure 2. In this figure, there are two cycles namely ORC shown by red lines and Refrigeration cycle shown by blue lines. In this ORC system, refrigeration cycles was used only to hold isothermal condition of water in condenser. Each step of the systems was equipped with pressure gauge and thermocouple to measure pressure and temperature of fluid in a tube when system operates. In addition, a flow meter was used to measure the mass flow rate of the fluid.

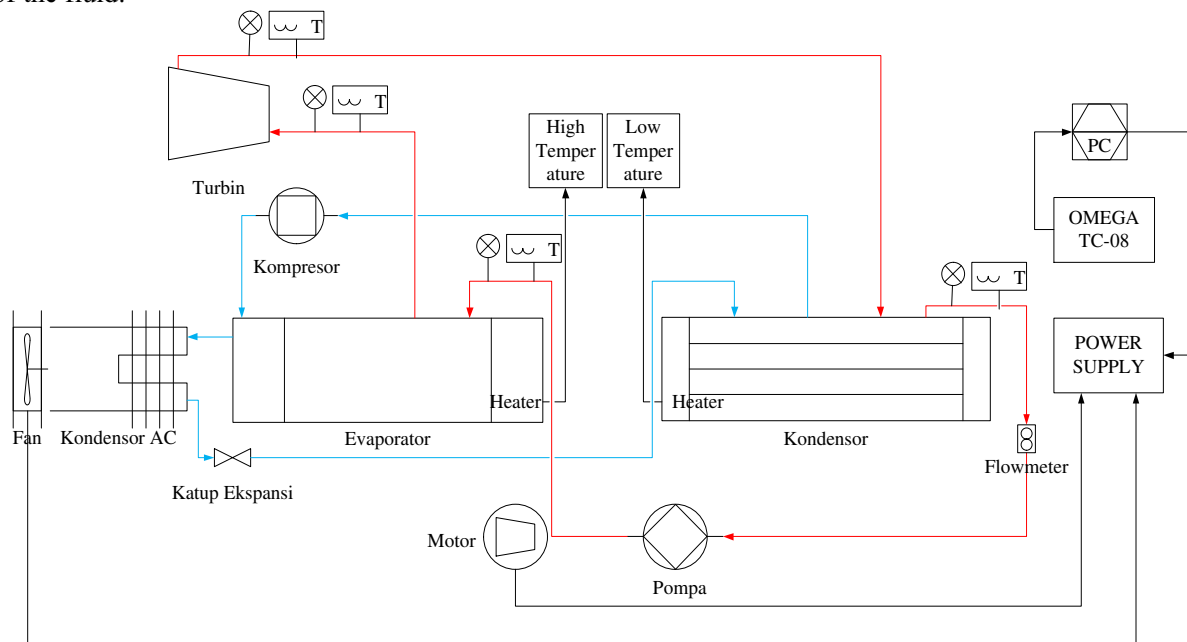


Figure 2. Schematic of ORC System

5. Design Parameter

The design of evaporator and condenser was calculated using the equation that described previously by Cengel [14] as follows:

$$Q_h = Q_c = \dot{m} \cdot \Delta h = U \cdot A_s \cdot \Delta T_{lm} = U \cdot A_s \cdot \frac{\Delta T_1 - \Delta T_2}{\ln \left(\frac{\Delta T_1}{\Delta T_2} \right)} \quad (3)$$

To determine the rate of heat transfer for laminar flow is

$$h = \frac{k}{D} Nu = \frac{k}{D} \left(3,66 + \frac{0,065 \left(\frac{D}{L} \right) Re Pr}{1 + 0,04 \left[\left(\frac{D}{L} \right) Re Pr \right]^{\frac{1}{3}}} \right) \quad (4)$$

and for the turbulent flow is

$$h = \frac{k}{D} Nu = \frac{k}{D} (0.023 \times Re^{0.8} Pr^{1/3}) \quad (5)$$

6. Result and Discussion

Design simulation in Cycle Tempo 5.1 was described in Figure 3:

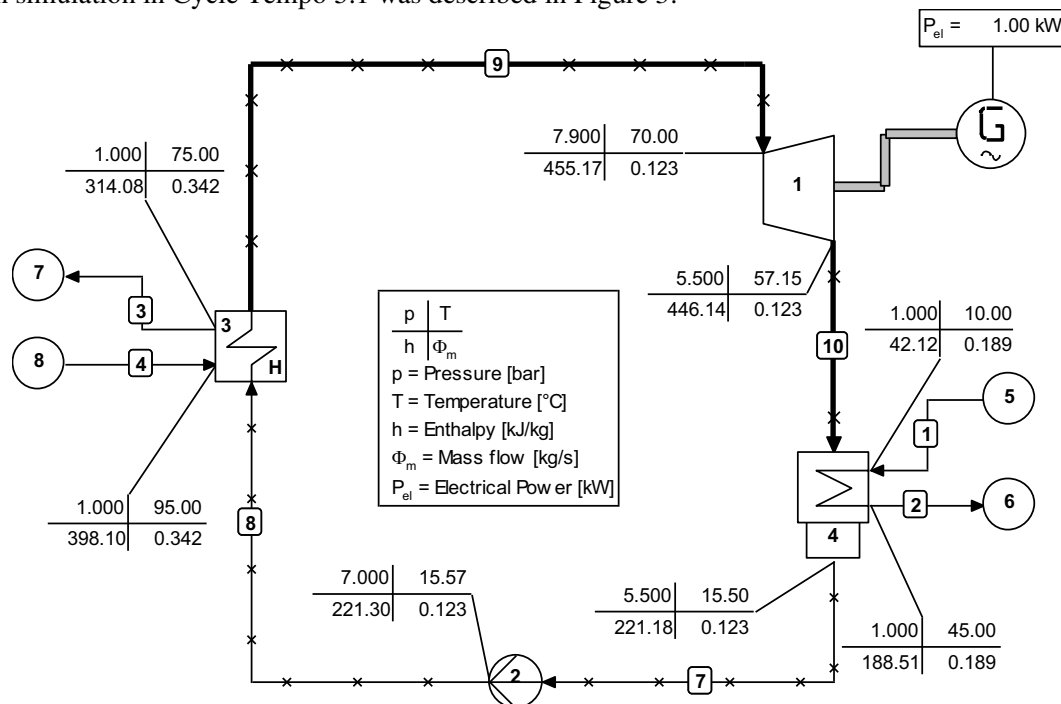


Figure 3. Design Simulation of ORC

Based on the data obtained from Figure 3, then to determine the design of evaporator and condenser was used design parameter equation as Eq. 3, Eq. 4, and Eq. 5 with other parameters as follow:

1. Power generator	: 1 kW	6. $R_{f,o}$: $0.0004 \text{ m}^2 \cdot ^\circ\text{C} / \text{W}$
2. Do tube	: 0.009525 m	7. K copper	: $385 \text{ W/m} \cdot ^\circ\text{C}$
3. Di tube	: 0.008407 m	8. Flow type	: Parallel-flow
4. U	: $300 \text{ W/m}^2 \cdot ^\circ\text{C}$	9. HE type	: Shell-and-tube
5. $R_{f,i}$: $0.0002 \text{ m}^2 \cdot ^\circ\text{C} / \text{W}$	10. Type of tube	: Helical tube

The result of design shown in Table 3, helical tube of evaporator and helical tube of condenser shown in Figure 4 as follow:

Table 3. Data from the design

Tube	Length (m)	Helical diameter (m)	Pitch (m)	Number of Coil	Height of helical (m)
Evaporator	10.61	0.25	0.0222	13.5	0.3
Condenser	10.56	0.25	0.0222	13.5	0.3

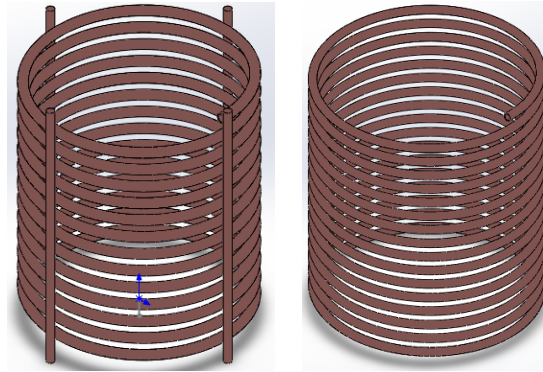


Figure 4. Helical Evaporator (a); Helical Condenser (b)

Thus, final result of this ORC system design shown in Figure 5 and Table 4 as follow:



Figure 5. ORC system

Where:

- | | |
|---------------------------|--|
| 1. Pump | 7. Compressor as turbine |
| 2. Motor | 8. Evaporator |
| 3. Condenser | 9. Flowmeter |
| 4. Temperature Controller | 10. Compressor for refrigeration cycle |
| 5. Pressure Gauge | 11. Refrigeration condenser |
| 6. Thermocouple | |

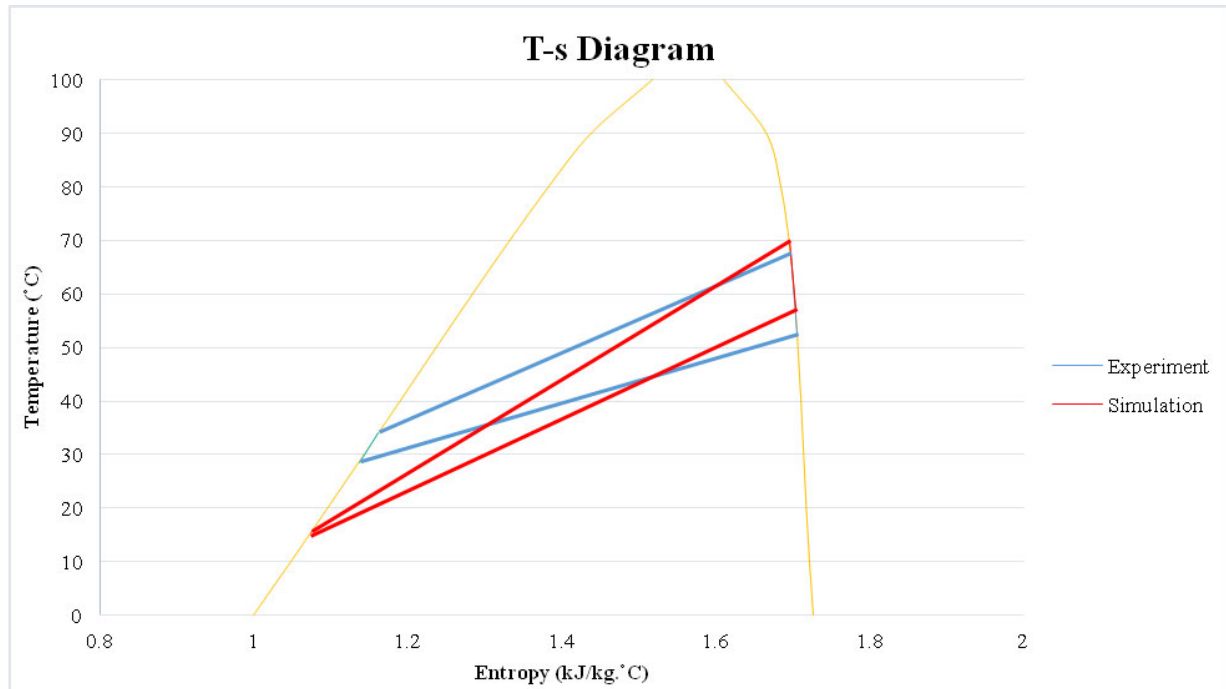


Figure 6. T-s Diagram of R134a

There is a difference between the design and experiment results, where in the design, the inlet pressure of pump of 0.55 MPa and the inlet pressure of turbine of 0.79 MPa resulted the efficiency of 3.8%, whereas in experiment, inlet pressure of pump of 1 MPa and inlet pressure of turbine of 1.25 MPa, the efficiency of 3.33%. We can see in the figure, the blue line describes cycle of R-134a of experiment, red line describes cycle of R-134a of design. The difference of inlet pressure both of components can affect the power generated of turbine. High inlet pressure of turbine will generate the turbine well. From the figure, we can see that curve that has a larger area has a higher efficiency, so curve which has greater efficiency is simulation shown in red line. Otherwise, the design of system was made in ideal conditions, whereas in the experiment that there are many energy losses in each process. This causes the difference in efficiency between design and experiment.

Table 4. Comparison of Design and Experiment Result

	W,t (kJ/s)	W,p (kJ/s)	Q,in (kJ/kg)	W,net(kJ/kg)	Efficiency (%)
Design	1.11	0.12	233.87	8.91	3.8
Experiment	0.614	0.334	197.89	6.59	3.33
	0.310	0.169			

The conclusion of this study is Organic Rankine Cycle system has been successfully designed and manufactured using R-134a working fluid with helical tube of evaporator and helical tube of condenser. Where, the length of helical evaporator is 10.61 m and helical condenser is 10.56 m. Based on the design,

this study had resulted power turbine of 1110 Watt and efficiency of system of 3.8%, whereas result of the experiment is power turbine of 614 Watt and efficiency of system of 3.33%

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