Design of heat exchanger to evaporate for R134a working fluid in organic Rankine cycle power plants system

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Abstract. Design for a power plant from the organic Rankine cycle (ORC) system is a power generation technology from one of the applications of renewable energy in the field of electricity. In this study, we applied a design of an organic Rankine cycle system in the form of a heat exchanger device installed in an ORC system that functions to change the form of the working fluid that is R-134a into steam or liquid. Heat exchangers are designed to be shaped like a drum or vessel with dimensions of 60 centimeters in height and 50 centimeters in diameter. This heat exchanger is made of two pieces to support the main components of the ORC system, namely the evaporator and condenser components. This heat exchanger design can produce temperatures below 10 °C in the condenser to change the shape of the working fluid to become liquid and can also produce temperatures above 90 °C in the evaporator with the form of a working fluid in the form of steam or gas. From each heat exchanger is given insulation or wrapped so as not to cause heat propagation either out or air, the temperature of the incoming environment is coated with aluminium foil and foam with a thickness between 1-2 centimeters.

1. Introduction

Technology in the field of electricity generation from the organic Rankine cycle (ORC) system has become increasingly popular for researchers in various countries, especially developed countries such as Japan, European countries, China, America and other countries. As with Japanese researcher N. Yamada to do conducted an experiment on the use of a Rank cycle type cycle tool called (PRC) and also used expander as electricity production as an organic Rankine cycle system [1]. The use of a pump less model that uses a compressor scroll as an expander manages to produce 20 watts of electricity. Then the Chinese researcher J.C. Chang to do for focus on the compressor scroll experiment used as an expander in the application of organic cycle systems at low temperatures with the working fluid used is a R245fa refractor [2]. Another researcher from Belgium S. Quoilin is conducted an ORC experimental activity using a scroll compressor as an expander which circulates its working fluid is the HCFC-123 refrigerant which has the aim of its research which is to compare the predicted results with the results of reality [3]. From several ORC researchers described above, the ORC plant is very promising to be developed and can be applied in remote areas that are difficult to reach by electricity networks. In our research, it is designed from one of the main components of the ORC system power plant, namely heat exchanger, in which the exchanger will later function to take or release heat in the main components of the ORC system. There are some researchers who carried out the experiment of the ORC system generator by
modifying the vehicle's compressor scroll AC as an expander using the working fluid R-245fa [4,5] and R-123 [5,6], but in our experiment even though the expander is the same the modification of the scroll AC compressor for fluid works using environmentally friendly refrigerant is R134a. By using the working fluid R-134a for the results of thermal efficiency on the operation of the ORC system it can produce a significant amount between 2.4 - 2.5%. As for this study planned in processing the results of the data carried out only reached how much thermal efficiency occurred in this experiment.

2. Description of experiment
In our experiment is to fulfil the requirements of the main components and other supporting equipment to conduct an ORC power plant experiment system. Components that are fulfilled include: condenser and evaporator using plate heat exchanger type, then working fluid pump with 3 phase specifications and 1600 rpm rotation. The expander used as a turbine is a scroll air conditioning (AC) compressor with a volume of 97.8 cc/rev and a component of hot water production which is a combination of heaters and a 1000 watt heat exchanger. Then design the experiment equipment, then the installation process of the main tools and other supporting equipment and operate the experimental equipment, but first check one by one on all the main components so that the experimental equipment operates properly and perfectly. This ORC experiment picture looks like the one shown in the flow chart below.

![Flowchart for ORC experiment.](image)

For the diagram of the main components and supporting other equipment in the ORC experiment shown in Figure 2 below. In Figure 2 shows that the working fluid flows past the main components, among others, passing through the condenser and evaporator which uses a plate heat exchanger (PHE) in this
case each serves as a heat transfer at low temperatures to high temperatures or vice versa from high temperature to low temperature. At the evaporator, the working fluid, R134a, is evaporated by flowing hot water at a temperature that has been determined according to the plan. Likewise on the condenser, the working fluid is liquefied or saturated by a temperature-cooled cooling system. For a diagram of the main components and other supporting equipment in the ORC experiment shown in Figure 2 below.

Figure 2. Diagram experimental for ORC.

Furthermore, for the concentration on the ORC design is focused on the design dimensions of the heat exchanger that enables the evaporator and condenser which are an important part of the operation of the experiment. The shape of the heat exchanger dimension is 50 cm in diameter and 60 cm in height as seen in the figure 3 below.

Figure 3. Heat exchanger for evaporator and condenser.

The heat exchanger in the form of a drum is made by two units to increase the temperature of fresh water in the evaporator so that evaporation occurs in the working fluid. Then the other heat exchanger is used to melt the working fluid in the condenser.

3. Equations for ORC research

This data processing estimate for ORC research requires several supporting equations from references such as textbook and papers relating to heat transfer, thermodynamics and the theory of Rankine cycle.
theory. These equations will be conveyed using the P-h diagram for the R-134a working fluid as shown in Figure 4 below.

Figure 4. P-h Diagram for ORC cycle.

In Figure 4 above this is explained which in the work process of the ORC diagram using this P-h diagram at point 3 shows that the operation of a working fluid pump that sucks fluid will come out of the condenser and then flow to the evaporator by giving the pump working rate equation as follows:

\[ W_{\text{Pump}} = \frac{m_{\text{fluida}} \cdot (h_{\text{Pump.out}} - h_{\text{Pump.in}})}{\eta_{\text{pump}}} \]  \hspace{1cm} (1)

\[ W_{\text{Pump}} = h_4 - h_3 \]  \hspace{1cm} (2)

Where \( W_p \) is the power that enters each mass unit by passing the pump. Furthermore, in the refrigerant evaporation process occurs in the heat exchanger which is combined with one package with a heater to produce hot water. Hot water will release heat in the flow of the refrigerant pipe in the evaporator at conditions 4 and 1 so that the refrigerant will occur the process of changing form from liquid to gas and the process of changing the thermal form is the balance of mass and energy rate given the following equation.

\[ Q_{\text{in}} = h_1 - h_4 \]  \hspace{1cm} (3)

Where \( Q_{\text{in}} \) is the rate of heat transfer from the energy source into the working fluid per unit of mass through the evaporator and the refrigerant vapor flows to the expander. Then the steam of R-134a refrigerant coming out of the evaporator at point 1 with high temperature and pressure conditions will expand to rotate the expander to produce work and then discharged to the condenser in point 2 with a relatively low working fluid vapor pressure. For heat transfer around the expander is not taken into account, then the equilibrium rate of mass-energy around the expander is given the following equation.

\[ W_{\text{Exp}} = h_1 - h_2 \]  \hspace{1cm} (4)

Where \( W_t \) states the rate of work produced per unit of steam mass through the expander. In the condenser under conditions 2-3 the heat is taken up in the refrigerant flow pipe by the cooling water pipe with a certain temperature and amount of heat. The energy equation in the condenser is given as follows.

\[ Q_{\text{out}} = h_2 - h_3 \]  \hspace{1cm} (5)
Where $Q_{\text{out}}$ is the rate of energy transfer from the working fluid to cooling water per unit of fluid mass that works through a condenser. Thermal efficiency is used to measure how much energy goes into refrigerant by giving the following equation.

$$\eta_{\text{th}} = \frac{(w_{\text{exp}} - w_{\text{pump}})}{Q_{\text{in}}} = \frac{((h_1 - h_4) - (h_2 - h_3))}{(h_1 - h_2)}$$  \hfill (6)

Then the heat that is lost to the environment so that heat ($Q_{\text{in}}$) is very necessary in the heat transfer process which is increasingly embattled but the thermal efficiency is reduced. This condition can occur due to irreversibility in the pump and expander so that the work ($W_{\text{p}}$) needed is greater and the expander produces more work ($W_{\text{exp}}$).

$$\dot{m}_{\text{cond}} \times (h_2 - h_3) = \dot{m}_{\text{eva}} \times (h_1 - h_4)$$  \hfill (7)

In equation 7 above shows the mass balance of the working fluid at the average mass flow of the condenser and the average mass flow of the evaporator in the ORC system.

4. Results and discussion

Our experiment is selected the type of working fluid R-134a which is generally used as a working fluid for refrigeration systems or air conditioning to reduce the temperature of the room or freeze a liquid. While in this ORC research the function of R-134a is as a working fluid that gives momentum to the expander which results in spinning and produces a torque force that will couple the generator to produce electricity. The working fluid specifications used in this experiment are given as follows:

| Table 1. Property of R134a. |
|-------------------------------|
| **Characteristics** | **Conditions** |
| Boiling Point | -14.9 °F or -26.1 °C |
| Auto-Ignition Temperature | 1418 °F or 770 °C |
| Ozone Depletion Level | 0 |
| Solubility In Water | 0.11 % by weight at 77 °F or 25 °C |
| Critical Temperature | 252 °F or 122 °C |
| Cylinder Color Code | Light Blue |
| Global Warming Potential (GWP) | 1200 |

Before doing the experiment, it is necessary to measure the parameters of the instrument at the heater temperature and also on the cooling system using a refrigeration system. The parameter settings are given in table 2 below.

| Table 2. Temperature settings in the heater and cooling system. |
|-----------------------|
| **No.** | **Apparatus** | **Temperature (°C)** |
| 1. | Heater | 100 |
| 2. | Cooling System | 20 |

The experimental results obtained based on the temperature setting in the evaporator and in the condenser make the shape of the graph as shown in Figure 5 below.
In Figure 5 above shows that of some of the main components ORC experimental equipment that is operated that is the result of all temperatures occurring has increased both in the condenser, expander, evaporator and at the working fluid pump.

In Figure 6 above is the highest temperature is in one of the main components of the ORC in evaporator with a temperature of up to 78 °C which is in accordance with the planning of the heat exchanger temperature setting for the evaporator that is at the setting of 80 °C. There was an increase in thermal efficiency to reach a significant is 2.5 %.
In Figure 7 above shows that the energy produced by the heat exchanger to evaporate the working fluid that can reach 412 kJ/kg which occurs at the temperature conditions in the evaporator is between 90 – 95 °C.

In Figure 8 above shows that the energy produced by the heat exchanger to dilute the working fluid which can reach 253 kJ/kg which occurs in the temperature conditions in the condenser between 28 – 30 °C.

5. Conclusion

From the operation of the ORC experiment that has been carried out by setting the heat exchanger that is designed on the condenser with a temperature of 20 °C and setting the temperature at the evaporator at 100 °C, then obtained thermal efficiency for the ORC experiment system equipment operation ranges from 10 %. Then the energy needed in the evaporator is 412 kJ/kg at a temperature between 90 – 95 °C and the energy needed in other ORC main components, namely the condenser requires energy of 253 kJ/kg at temperatures between 28 – 30 °C and there was an increase in thermal efficiency to reach a significant is 2.5 % for ORC system in part of evaporator as one of main component.
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