Design of a combination package of heat exchanger and heater for organic rankine cycle power plant

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Abstract. This paper presents the capacity of a heat exchanger with a plate heat exchanger model as evaporator and condenser to liquefy and evaporate R-134a refrigerant as the working fluid in a power plant system by operating an Organic Rankine Cycle (ORC) system using a scroll type expander. The evaporating and liquefying refrigerant as the working fluid uses hot water at a temperature between 40 ^{0}C - 80 ^{0}C and an evaporator inlet temperature at between 24.1 ^{0}C – 28.5 ^{0}C. The model design of the hot water production system is a combination of heat exchanger and heater with a shell and tube construction, where the heater is immersed in the heat exchanger. Experimental results show that the average revolutions of the turbine expander scroll is about 348.2 rpm and thermal efficiency between the evaporator and condenser as the heat exchanger ranges from 2 % to 8.5 %.

1. Introduction

Nowadays there is a rapid development of power generation technology that uses the basic theory of Organic Rankine Cycle system (ORC), especially in small scale power plants that range from 1 - 5 kW. Research on ORC by Sylvain Quoilin et al., used a scroll compressor as an expander to circulate working fluid HCFC-123 with the purpose of comparing predicted results with real results [1]. Researcher Mingshan Wei et al., conducted small scale experiments on waste heat recovery using strict Organic Rankine Cycle system rules and showed that flow loss has a great effect on the suction scroll expander [2]. Another researcher, Janette Hogerwaard et al. [3] conducted an experiment on heat engines to control heat at low temperatures aiming to measure power and effective heat production for small-scale applications. The system processes used renewable energy such as biomass / biofuel / biogas combustion, geothermal heat, solar and industrial waste heat with the R134a refrigerant with a low temperature heat source below 150 ºC. Researcher Noboru Yamada et al. [4] conducted experiments using the Pumpless Rankine type cycle tool called (PRC) and also used the expander for the production of electricity as an organic rankine cycle system. His research used the pumpless model scroll compressor type expander to produce 20 watts of electricity. Jen-Chieh Chang et al. [5] focused on compressor scroll expander experiments that can be applied to low temperature organic cycle systems. This research used refrigerant R245fa as the working fluid and two compressors to determine the difference of volume ratio. The maximum power output from the expander is 1.77 kW while the amount of electricity delivered to the generator is 1,375 kW.

2. Research Methodology

This study focuses on the design of a package of heater and heat exchanger with a diameter of 38 cm and height of 50 cm. The 1200 watt electricity heater reaches an evaporator temperature of 80°C. The heater serves to heat the water which channeled to the plate heat exchanger (PHE) to heat the refrigerant that will evaporate at temperature and pressure conditions specified in the ORC system. The evaporator, which is one of the main components in the ORC system, uses low temperatures. The detailed diagram of the system and the flowchart of the experiment as follows.
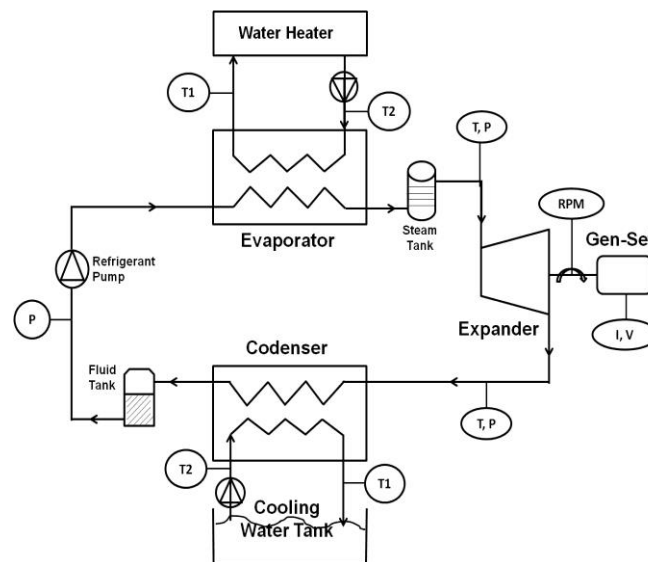
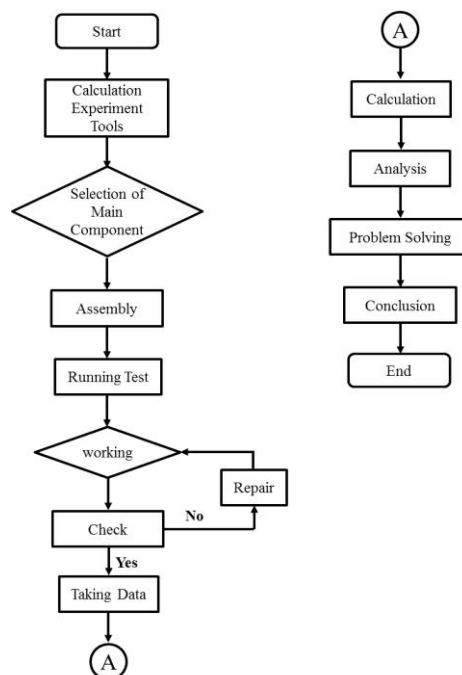**Figure 1.** Diagram Cycle for Organic Rankine Cycle

Figure 2. Flowchart of ORC Experiment

For the purpose of simplifying analysis, complicated and complex heat transfer can be avoided between the generating component and its surroundings. Changes in kinetic and potential energy are also ignored. Each component is considered to be stable. By using the principle of mass conservation and energy conservation along with the idealization, equations for energy transfer are designed for each of the generating components. The main components used in this research are the Sanden type TRSE09 expander, the Kaori type K70 condenser and evaporator and Motor pump 3 phase with 1600 rpm as the refrigerant pump working fluid. Here follows an explanation of the basic Organic Rankine Cycle work process theory using T-s diagram.
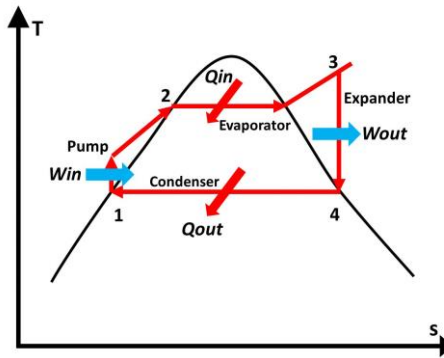

Figure 3. Diagram of ORC cycle

2.1. Working fluid pump
At point 1 the refrigerant pump applies suction and pressure to refrigerant R-134a which increases the pressure so that it moves from the condenser towards the evaporator. It is assumed that no heat transfer occurs around the pump and there is an equilibrium equation of mass and energy rate as follows.

$$Q - w = \left((h_3 - h_2) + \frac{(v_1{}^2 - v_2{}^2)}{2} \right) + g\,(z_4 - z_3) \tag{1}$$

or
$$w_p = h_2 - h_1 \tag{2}$$

Where w_p is the incoming power per unit of mass through the pump

2.2. Heater as producer of hot water for evaporator
The evaporation process of the refrigerant occurs in the heat exchanger which combines with a heater to produce hot water. Hot water releases heat to the refrigerant pipe in the evaporator at points 2 and 3 enabling the refrigerant to change state from liquid to gas. The thermal change process is the equilibrium of mass and energy rate as given in the following equation,

$$Q_{in} = h_3 - h_2 \tag{3}$$

where Q_{in} is the rate of heat transfer from the energy source into the working fluid per unit of mass through the evaporator, and then the refrigerant vapor flows to the expander.

2.3. Expander scroll as turbine
The refrigerant vapor 134a that exits the evaporator at point 3 has high temperature and high pressure which will expand to rotate the expander to create work before discharging it to the condenser at point 4 with relatively low vapor working fluid pressure. Heat transfer around the expander is not calculated, so the equilibrium mass energy rate around the expander is given in the equation,

$$w_t = h_3 - h_4 \tag{4}$$

where w_t denotes the rate of work produced per unit of vapor mass through the expander.

2.4. Condenser
At point 4 - 1 the condenser takes heat from the refrigerant flow pipe through a cooling water pipe at a specific temperature and amount of heat. The energy equation for the condenser is given as follows.

$$q_{out} = h_4 - h_1 \qquad (5)$$

where, q_{out} is the rate of energy transfer from the working fluid to the cooling water per unit of fluid mass working through the condenser. Thermal efficiency is used to measure how much energy enters the refrigerant by the following equation.

$$\eta_{th} = \frac{(w_t - w_p)}{Q_{in}} = \frac{(h_3 - h_4) - (h_4 - h_3)}{(h_1 - h_4)} \qquad (6)$$

There is heat loss into the environment so heat (Q_{in}) is needed to increase the heat transfer process while thermal efficiency is reduced. This condition occurs due to the irreversibility of the pump and expander so that as greater work is required (W_{in}) the expander produces more work (W_{out}) .

Table 1. Properties 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

3. Preparation for ORC experiment

Equipment & devices created for the ORC experiments use several components that relate to electricity generation and refrigeration work processes. The components used in the ORC consist of working fluid pump, plate heat exchanger as an evaporator and condenser, a heater and heat exchanger drum, cooling water drum liquid receiver, oil water separator and a control panel. Installation of these components is performed in several steps:

- Step 1: calculate piping and connections required such as napples and nuts to link the main components mentioned above before installation.
- Step 2: install and connect pipes that serve as a liaison between the main components with valves and nuts and perform any welding required.
- Step 3: after all components are installed and connected with the pipe, conduct test runs and collect data.

The heater and heat exchanger drum seen in figure 5 is 38 cm in diameter and 50 cm in height. This heater produces hot water which is used to vaporise the working fluid in the evaporator to the desired amount of volume. Hot water re-enters the heat exchanger drum and circulates constantly.
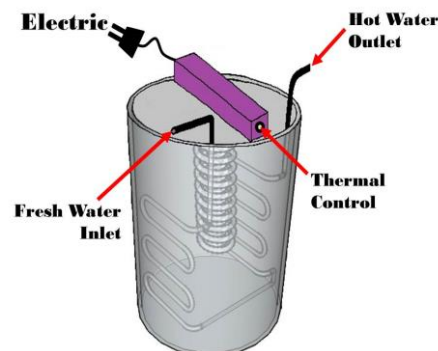

Figure 4. ORC experiment equipment **Figure 5.** Combination packet of heater & heat exchanger

4. Result and Discussion

The design of combining a heater and heat exchanger device in the form of a drum begins with setting the heater temperature at between 40 ºC – 80ºC, then determining data for the inlet temperature into the evaporator, the amount of pressure in the expander and the number of expander rotations generated by this ORC system. The first step is to calculate the energy values from the evaporator, condenser, and expander. Then, data from the measuring equipment and from data acquisition are collected and processed.

Finally, the flow of working fluid is assumed to equal the airflow measurement at the expander and a wind compressor measures pressure and fluid flow in the superheat phase of 1.38 Bar and 0.006 kg / s, while the working fluid mass at liquid state is 1 kg / S. Results from data processing is used to record evaporator inlet (ºC) temperatures every second up till 15 seconds as shown in figure 6. Next, the data on vapor pressure of working fluid (psi) in the expander is shown in figure 7 using the same time parameters. Data for measuring temperatures are obtained by using a thermocouple which is connected to a data logger to record all measurements. And figures 6 and 7 show the working fluid temperature variation between 24 ^{0}C to 28.5 ^{0}C on the variations of temperature control settings between 40 ^{0}C - 80 ^{0}C and the working fluid pressure entering the expander between 120 psi to 175 psi.
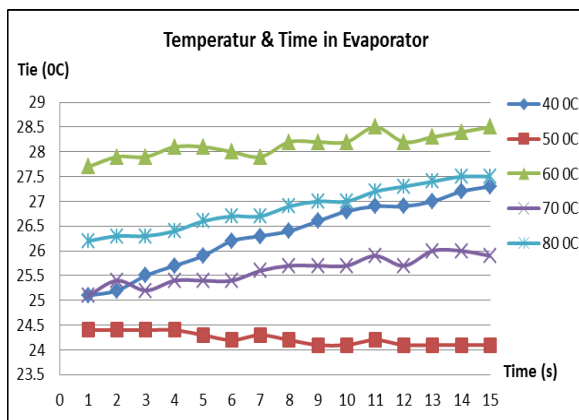

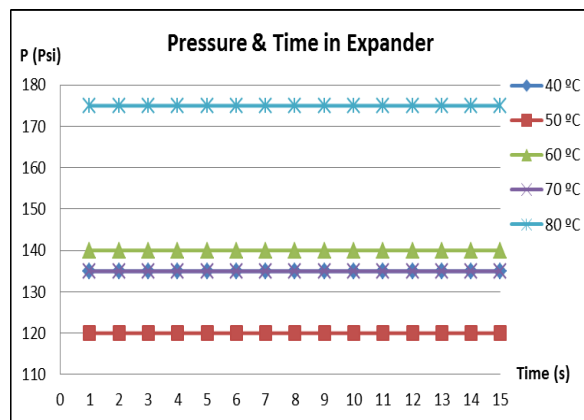**Figure 6.** Temperature & time in evaporator

Figure 7. Pressure & time in expander

Figure 8 shows how the rotating expander produces various pressure variations that occur between 316.7 rpm to 377.9 rpm with heater temperature settings between 40 ^{0}C to 80 ^{0}C.
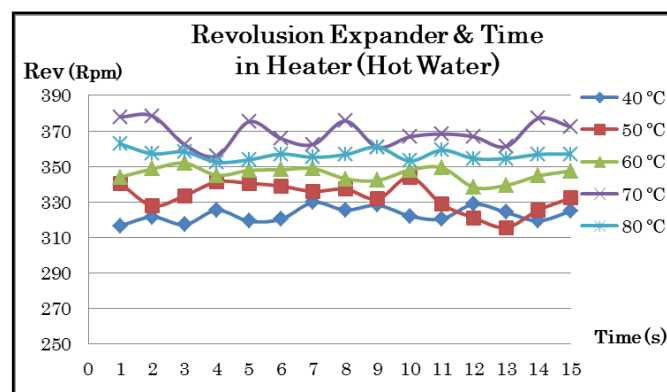

Figure 8. Variations of expander revolutions and time in the heater (hot water)

The calculated thermal efficiency of heater settings between 40 ^{0}C - 80 ^{0}C that produce hot water to create energy and work can be shown in table 2.

Table 2. Values of energy, power, and thermal efficiency in each temperature variation

No.	T_{heater}	Q_E	W_P	W_E	Q_C	ηth
1.	40	185.87	1.4880	0.03	182.10	2.0%
2.	50	200.89	1.4893	0.05	194.66	3.1%
3.	60	203.02	1.5220	0.07	193.13	4.9%
4.	70	218.53	8.6547	0.10	206.00	3.7%
5.	80	222.79	3.1893	0.13	203.91	8.5%

5. Conclusion

The Organic Rankine Cycle system experiment has enough data to determine the performance of the system. The experimental results show that based on the heater temperature set between 40 ^{0}C and 80 ^{0}C the inlet temperature of the evaporator is between 24.1 ^{0}C and 28.5 ^{0}C, while the vapor pressure of the working fluid entering the expander is between 120 psi to 175 psi. Some parameter results show the average expander rotation is 348.2 rpm and thermal efficiency is between 2 % - 8.5 %.

6. Acknowledgement

7. References

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