Experimental study of an organic rankine cycle system using r134a as working fluid with helical evaporator and condenser

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Abstract. Organic Rankine Cycle (ORC) system is a modification of the conventional Rankine cycle to generate electricity from the utilization of low-grade temperature heat sources. Experiment on ORC systems was conducted to analyse the performance of a small scale ORC system with 1 kW capacity using R134a as working fluid. A helical type of evaporator and condenser were used as heat exchangers and a scroll type car compressor was used to generate power with variation in heat source temperatures of 75 oC, 85 °C, and 95 °C. Turbine power is calculated theoretically based on the experimental data obtained due to the turbine was not able to rotate. This experiment results show the optimum efficiency and theoretical power of ORC is respectively 3.33% and 279.58 Watt with inlet pressure and temperature of turbine are respectively 1.25 MPa and 67.7 °C.

1. Introduction

Rapid population growth and industrial development have an impact on increasing world energy demand, especially electrical energy [1]. Fossil energy consumption for steam power plant has been widely used in many countries around the world because of the ease in getting it to suffice human needs in large numbers. About 40% of the electricity generated worldwide comes from power plants with coal fuel [2, 3]. Power plants with larger production capacity require a large supply of coal, while coal supplies nowadays around the world are dwindling due to increasingly higher demand. Coal-burning gas is the largest source of greenhouse gas (GHG) emissions that can lead to climate change problems [3]. Therefore, it becomes the reason for energy sector researchers to be able to lower the dependence on fossil energy and to develop low temperatures heat sources potential that has not been currently practiced optimally [4]. Based on data from the International Energy Agency (IEA) in 2014, the use of coal fossil fuels accounted for 44% of total CO2 emissions worldwide. Coal burned in a steam power plant also produces a number of harmful pollutants such as NOx, SO2, SO3, mercury, arsenic, and radioactive particle which are harmful to human health and environment [4, 5]. Air pollution caused by coal combustion leads to an increased risk of lung cancer, stroke, heart disease, premature birth and respiratory diseases [2, 6].

Because of those adverse effects of coal use, the most important step to be taken now is by replacing coal-fired power plants with renewable energy resources such as mini and micro hydro, geothermal, wind energy, solar cell and utilization of industrial waste heat [7]. Moreover, countries around the world are developing the concept of clean energy, especially for power plant, that is Clean Power Plant (CPP) to reduces CO2 emissions by coal-fired power plants in 2030 by 30 % and encourage more environmentally use of renewable energy [8]. In Indonesia, renewable energy such as geothermal has the greatest potential to be developed. Geothermal energy potential in Indonesia is 40% of the total worldwide but its current use is only 4% [2, 9]. Some causes for the underdevelopment of geothermal power plants are due to high operational costs and the type of most geothermal energy in Indonesia is low-grade temperature. Thus other innovations must be applied to overcome the low temperature problem. Among the solutions is utilization of geothermal energy for power plant with Organic Rankine Cycle System (ORCs).
Organic Rankine Cycle (ORC) system is a modification of the conventional Rankine cycle to generate electricity from the utilization of low-grade temperature heat sources. This technology does not require coal-fire which means no CO₂ emissions are generated. Various studies on the application of the ORC system have been widely studied with varying sources of low temperature heat energy used. Research on possible use of geothermal energy for ORC from multiple hot springs with temperatures of 70-80°C throughout Indonesia using R227ea as working fluid was conducted [10]. Lompio-1 hot springs in Central Sulawesi, which has a temperature of 78°C with the largest mass flow rate of 3000 l/min, is capable of producing a turbine power potential of 130.13 kW. It can be concluded from the research that the mass flow rate from the hot springs has a significant effect on the electrical energy produced. Usman et al. and Yuh-Ren et al. [4, 11] conducted an experimental design and review for application of ORC system with R245fa as working fluid and utilization of waste heat from steam at temperature of 120°C that capable to generate 1.02 kW of electrical energy and thermal efficiency of 5.64%. The efficiency can be increased by insulating the piping system and increasing the evaporative temperature of the fluid in the evaporator. Yuh-Ren et al. [11] conducted experiments to determine the effect of vapor exit of the turbine by using plate-type and shell-and-tube evaporators on performance of ORC system. Results of the experiment showed that ORC system performance is more stable using evaporator with shell-and-tube type than of plate type. Nigusse et al. [12] conducted a research to determine the effect of shell-and-tube type condenser on the performance of geothermal power plant with ORC system, which showed that an increase in the flow rate of cooling water in the condenser results in the pressure drop of the working fluid in the condenser. It is thus increasing the incoming work on the pump that leads to decreasing the efficiency of the system. Hung et al. [13] presents a study of the application of a heat source in a ventilation system of solar thermal energy for the development of an ORC system and found that the maximum temperature generated by a solar thermal vent system is 120°C, with an efficiency of 6.2% when utilized for an ORC system. Another study presents the use of biomass heat sources from palm oil mill waste for the development of the ORC system and concludes that it is technically possible to produce higher thermal efficiency than the ORC basic system [14].

The selections of the working fluid employed should also consider the expansion component or turbine type to be used for the ORC system. The consideration must include the capacity, cost and complexity of manufacture and maintenance [15] as shown in Table 1 below.

### Table 1. Suitable Expansion Component Type for ORC System [15]

| Type               | Capacity (range) [KW] | Rotating Speed (type) | Cost | Advantages                                                                 | Disadvantages                                                                 |
|--------------------|-----------------------|-----------------------|------|-----------------------------------------------------------------------------|--------------------------------------------------------------------------------|
| Radial inflow tube| 50-500                | Low                   | High | Light weight, nature manufacturability and high efficiency                   | High cost, low efficiency in off-design conditions and cannot heat two-phase   |
| Scroll expander    | 1-10                  | ~5000                 | Low  | High efficiency, simple manufacture, light weight, low rotate speed and tolerable two-phase | Low capacity, lubrication and modification requirement                        |
| Screw expander     | 15-200                | ~5000                 | Medium | Tolerable two-phase, low rotate speed and high efficiency in off-design conditions | Lubrication requirement, difficult manufacture and cost                      |
| Reciprocating piston expander | 20-100 | ~5000 | Medium | High pressure ratio, simple manufacturing, adaptable in variable working conditions and tolerable two-phase | Many movement parts, heavy weight, have valves and torque impulse              |
| Rotative vane expander | 1-10     | ~5000                 | Low  | "Vibrate" two-phase, torque stable, simple structure, low cost and noise     | Lubrication requirement and low capacity                                       |

Oralli et al. [16] experimented with using a compressor scroll as an expander on the ORC system to observe the system performance, which concluded that the expander did not work optimally because there was no modification of the original function of the compressor for the turbine. Eicke and Smolen [17] presents a study of the trial use of a commercial scroll expander (Air Squared Inc., E15H22N4.25) for a 1 kW ORC system using the working fluid of R245fa and found that 17 kW of power was generated. The uses of commercial turbine expander with more promising performance are good but generally require larger cost.

From several studies that have been mentioned above, it is known that there has been not sufficient research on the ORC system with a variety of heat sources and types of heat exchangers used. More previous researches applied the use of heat exchangers with shell-and-tube type and plate type. Therefore, the use of heat exchangers with helical type for ORC system needs to be conducted in
experiments to obtain more information. This study will describe the performance of ORC system that using helical type heat exchangers with a capacity of 1 kW and working fluid of R134a. To function as expansion turbine, a car AC compressor with scroll type that has never been tested for a laboratory scale ORC is used for its low cost. This experiment will also observe the effect of temperature variations of the heat source to the inlet temperature and the inlet pressure of the expander, then calculate its effect on the efficiency of the ORC system.

2. Methodology
This section describes experimental set up, experimental preparation, and data collecting.

2.1. Experimental set up
Power plant with the ORC system has been designed and manufactured at Energy Conversion Laboratory, Department of Mechanical Engineering, University of Riau. ORC system has a generator capacity of 1 kW, the heat source is obtained from heated water by heater in evaporator and air conditioning system to cool water as cooling system on condenser. To keep the temperature constant in the heat exchanger, temperature controller Autonic TC4S was used to regulate heater and AC system. Working fluid used for ORC and AC systems were respectively R134a and R22. Temperature data recording was performed using K type Thermocouple that connected to data acquisition (DAQ) USB TC-08. Pressure measurements were performed manually using refrigerant pressure gauge Clause 1.6 that has measurement accuracy of 0.1 bar, fluid flow rate measurements were performed manually using water flow meter of Wierbock brand that has a measurement accuracy of 0.5 LPM.

Turbine expander used scroll type car compressor Keihin HS-090R to generate power. Heat exchanger helical (condenser and evaporator) and piping system of copper tube with 3/8 inch diameter were manufactured. ORC system used gear pump for ammoniac fluid with capacity of 1.08 m³/h, maximum pressure of 2.5 MPa, maximum head 25 meter and driven by Modern JY1A-4 1 pasha electric motor with power ½ HP, current 4.24 Ampere, voltage 220 V and maximum rotation of 1400 rotation per minute (RPM). The gear pump serves to drain the working fluid of the ORC system in order to rotate the turbine expander. Schematic and manufactured of the ORC systems can be seen in Figure 1.
2.2. Experimental preparation

Prior to the experiment, it is necessary to prepare the ORC system first to obtain accurate data. Water inside the evaporator tank that will be used as a heat source must to be heated by using a heater to reach a temperature in accordance with the experiment to be performed. Meanwhile, the AC system is also turned on to cool the water inside the condenser tank until it reaches a temperature of 10°C. Then turn on the temperature controller to keep the water temperature constant at the heat exchanger. When the desired water temperature of the heat exchanger has been reached, the pressure inside the system is lowered by a vacuum pump to a pressure of -30 bar and after that R134a is inserted into the ORC system slowly until the pressure is 5 bars. The last step is to turn on DAQ TC-08 then make sure the thermocouple can read correctly the temperature at each experiment point and set the time of recording temperature data for 20 minutes with a time interval of 1 second. Data collected can be start when all the experiment preparations have been completed.

2.3. Data collecting

Data collecting process can be started by running the gear pump and recording temperature data by DAQ TC-08. Data collecting of pressure is recorded manually by noting the value on the pressure gauge at each experimental point every 30 seconds. The same procedure is done to determine the rate of fluid flow flowing through the flow meter. During the data collection process, keep the heater and AC system on to condition the water temperature in each heat exchanger. The data is collected for 20 minutes until the temperature data recording on DAQ TC-08 ceased and after that the pump is turned off. The resulting temperature data will then be averaged every 30 seconds to adjust to the time of the pressure data and the working fluid flow rate. Data collecting process can be repeated using different temperature variations of different heat sources by resuming from the experiment preparation stage.

3. Results and Discussion

Experimental study was carried on a completed ORC system to determine its performance with variations of heat source temperature of 75°C, 85°C, and 95°C. After the data collecting, the quality of fluid and enthalpy at each experiment point will be checked using REFPROP 9.0. Turbine power is calculated theoretically based on the experimental data obtained because the turbine is not able to rotate. From the experiment, various heat source temperatures resulting in different efficiency of the ORC system. Efficiency of ORC derived from the 75°C heat source temperature can be seen in Figure 2.

![Figure 2. Efficiency of an ORC system at heat source temperature of 75°C](image)

Figure 2 displays the system performance of ORC efficiency at the heat source temperature variation of 75°C. There were only two valid data of the total data obtained during the experiment that can be used in calculation of the efficiency. At heat source temperature variation of 75°C, the highest efficiency that ORC system can produce is 0.47% at turbine pressure and temperature of 1.1 MPa and 57°C; while the increased turbine inlet pressure also increases the efficiency of ORC system. This condition occurred because condenser did not work optimally to reject heat from the working fluid after exiting the turbine thus the fluid quality is still superheated after passing the condenser. This is not desirable because it will
cause a decrease in the pump's ability to increase the fluid pressure flowing into the evaporator. Decreasing in evaporative pressure will affect the exit pressure of the evaporator to further enter the turbine and decrease the turbine work output and efficiency of the ORC system.

Figure 3. Efficiency of an ORC system at heat source temperature of 85 °C

Figure 3 displays the efficiency of the ORC system at 85°C heat source temperature which obtained the highest efficiency of 2.71% at turbine inlet pressure and temperature of 1.2 MPa 62.33°C, respectively. During the experiment, efficiency of the ORC system as a whole was decreased when turbine inlet pressure increased to 1.3 MPa. This phenomenon is caused by temperature of the heater water that did not conditioned which continued to decrease caused by the working fluid that has a cooler temperature than hot water, thus resulted a large temperature difference at the evaporator. It increases the heat input on evaporator. During the same process, the two different fluid temperatures in the evaporator also attempt to reach the equilibrium temperature, in addition to the heat wasted to the environment due to an evaporator that was not well insulated.

Figure 4. Efficiency of an ORC system at heat source temperature of 95 °C

Figure 4 shows the effect of turbine inlet pressure on ORC system efficiency at heat source temperature of 95°C which is the highest temperature variation used in this experiment. From the graph shown in Fig 4, the efficiency of the ORC system is fluctuating and unstable. At the beginning of the data collection, efficiency increased to an optimum point at 3.3% and turbine inlet pressure of 1.25 MPa. After that, turbine inlet pressure increases up to 1.35 MPa but overall ORC system efficiency has decreased significantly to 0.59%. This is due to increased turbine inlet pressure also resulting in an increase of fluid flow temperature thus causes condenser heat output to increase, decreasing on net heat of the system and also decreasing in the thermal efficiency of ORC system.
Figure 5 displays the effect of turbine inlet pressure on the turbine power of the ORC system. From the experimental data results with variations of the heat source temperatures, turbine inlet pressure increases with time. However, it makes the power generated by the turbine to decrease. This phenomenon is caused by turbine power that is theoretically also determined by the pressure and temperature of the steam after passing the turbine. During the experiment, the temperature of the working fluid entering the turbine continues to increase, but the turbine is unable to reduce the pressure and temperature after steam expansion, that caused steam pressure and temperature after exiting the turbine is still high which affects the enthalpy value generated. The difference in enthalpy becomes smaller if turbine temperature increases without turbine ability to decrease pressure, then the longer operation time of ORC system, the more reduce in turbine power will be.

The highest efficiency of experimental data was idealized using Cycle Tempo to determine the percentage of successful experimental results based on ideal conditions. The comparison results of these two conditions can be seen in Fig 6 below.

Figure 6 shows the T-s diagram of the comparison of highest experimental results and idealized results using Cycle Tempo. It can be seen that the resulting performance idealization higher than the experimental results. After the idealization, it is known that the ORC system produces a thermal efficiency of 6.95%, which means that the best experimental results can only reach 52.1% of the ideal state. This is caused by the situation where the experimental data results showed an increase in fluid temperature through the pump which led to the required pump power to raise the fluid pressure. Some things that could be the cause of the rise in working fluid temperature is that the condensation process did not occur optimally in the condenser thus the pumped R-134a has a mixed quality of liquid and gas phase. Another factor that likely contributed to the experimental result is the ORC system that was designed using an ammonia pump. R-134a has smaller density from ammonia, thus the pump did not
working optimally and requiring greater power to increase the pressure. In order to avoid losses due to the work of the pump, pump designed specifically for fluid refrigerant should be used.

4. Conclusion

Research on ORC system with low temperature utilization temperature using R134a working fluid has been conducted with temperature variation of heat source of 75°C, 85°C, and 95°C and cooling water temperature stabilized at 10°C. Turbine power is calculated theoretically based on the experimental data obtained because the turbine was not able to rotate. This experiment resulted the optimum efficiency and theoretical power of ORC are respectively 3.33% and 279.58 Watt, inlet pressure of turbine are 1.25 MPa using heat source temperature of 95°C. However, the manufactured ORC system produces stable power if the heat source temperature is 85°C, meaning that under those conditions R134a used for the ORC system can work optimally. The highest experimental results realized with Cycle Tempo are known to achieve only 52.1% efficiency of ideal condition efficiency.

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