Performance analysis of low temperature heat source of organic Rankine cycle for geothermal application

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Abstract. Indonesia has a high potential energy resources from geothermal activities. Base on the report of Asian Development Bank and World Bank, the estimated of Indonesian hydrothermal geothermal resource considered to be the largest among the world. If it's can be utilized to produce the electric power, it's can contribute to increasing the electrification rates in Indonesia. In this study, an experimental studied of electric power generation, utilizing the Organic Rankine Cycle (ORC) system to convert the low level heat of hydrothermal as an energy source. The temperature of hydrothermal was modelled as hot water from water boiler which has a temperature range from 60 °C – 100 °C to heat up the organic working fluid of ORC system. The system can generated 1,337.7 watts of electricity when operated using R134A with hot water inlet temperature of 100 °C. Changing system working fluid to R245fa, the net power obtained increase to 1,908.9 watts with the same heat source condition. This study showed that the ORC system can be implemented to utilize low temperature heat source of hydrothermal in Indonesia.

1. Introduction
Electrical energy has a very important and strategic role to support the modern society and national development in Indonesia. Therefore the availability of electricity must be reliable, sustainable and environmentally friendly. In Indonesia, the demand of electrical energy is higher than the supply [1]. This situation has an effect on acceleration of development in Indonesia especially in remote area which is not reachable by electricity.

It has been known Indonesia has a lot of potential heat sources that can be developed into electrical energy, such as solar and geothermal energy. Among the various heat sources, a low-temperature heat source from geothermal is great interest to be developed as a solution to the fulfillment of energy needs in remote areas that possess it.

Organic Rankine Cycle (ORC) have widely been studied to harness low-temperature heat source that provide temperature ranging between 40°C and 200°C. An ORC has the same components as a conventional Rankine cycle, such as a pump to raise the pressure of the working fluid, an evaporator to absorbing the heat, turbine (or expander) to convert the heat energy contained in the working fluid to be shaft power and condenser to reject the heat from the working fluid. The major difference is the choice of the working fluid, ORC use organic component instead water. Lakewand Bolland [4] analyzed the power production capability and equipment size requirements for R134a, R123,
R227ea, R245fa, R290 and n-pentane. They used a subcritical Rankine cycle without superheating, specified the heat source temperature in the temperature range from 80°C to 200 °C and used the evaporator pressure as independent parameter. Their results show that the selection of working fluids depends on the type of heat source, the temperature level and the design objective. N-pentane can be either the maximum power output (turbine) or the smaller heat exchangers. It was shown that the maximum power is obtained for the optimal evaporator pressure. Furthermore, a working fluid may have the smallest turbine size factor but requires a large heat exchanger area. The authors concluded that an economic study is necessary to determine which working fluid is the most appropriate. Qiu et al. [2] gave an overview of expansion devices for micro-CHP ORC systems and concluded that both scroll and vane expanders are good choices for systems within the capacity range of 1-10 kW. In particular, scroll machines are well adapted to small-scale ORC applications and offer significant advantages such as reliability and robustness (reduced number of moving parts), as well as ability to handle high pressure ratios and can handle the presence of a liquid phase in the flow.

The objective of this experimental study is to analyse the performance of the designed electric power generation, utilizing the Organic Rankine Cycle (ORC) system to convert the low-temperature heat of geothermal in form of hydrothermal as an heat energy source to be shaft power, and the system performance will compared with using two different working fluid such as R134a and R245fa.

2. System Description
The designed Organic Rankine Cycle (ORC) system consist of three loops, as can be seen in Figure 1. The first loop is the refrigerant loop, in this loop, the liquid refrigerant as a working fluid (R134a or R245fa) is pressurized by the feed pump. The pressurized liquid than heated in the tubing of the evaporator by the hot water that circulate in the evaporator shell until change the phase to be saturated vapor. The fluid leaves the evaporator in dry saturated condition and enters the modified scroll compressor as an expansion device. The expansion process drives an electrical generator to produce electric power. Leaving the expander, the working fluid enter the condenser to be cooled by the cooling water until change the phase to be saturated liquid and than pump again to the evaporator. The second loop is the heat source loop, in here, the hot water from the water boiler (simulating of low-temperature hydrothermal heat source) circulate to the evaporator. And the third loop is cooling water loop, in here, the cooling water circulates to absorb heat from working fluid in condenser and than reject the heat in the cooling tower.

![Figure 1. Schematic diagram of ORC System.](image-url)
3. Methodology

3.1 Experimental Set-Up

Based on a required condition, an small-scale ORC power generating was designed, constructed and tested. Figure 2 is the schematic diagram of the experimental system. The experimental prototype is mainly comprised of an evaporator, a water boiler, a gas tank, an expander, a throttling valve, a condenser, a liquid tank, an feed pump, a cooling tower, two water pumps and the interrelated measurement and data acquisition system.

A vane pump is used to feed and pressurized the working fluid. It can provide maximum operating pressure of 28 bar and rotational speed of 1200 rpm. The working fluid mass flow rate set to be 450 kg/h for all level of heating temperature.

The water boiler was used to simulated the hydrothermal heat source. The hot water from water boiler was supplied to heat up the working fluid in the evaporator coil pipes use a hot water pump with constant mass flow rate of 2000 kg/h and the hot water temperature varying between 60 °C to 100 °C.

After heat up in the evaporator, the superheated working fluid vapor collect in to the gas tank temporarily whose volume is 10 litres and the allowable working pressure is 30 bar. The use of gas tank makes the expander inlet pressure much more stable.

In the expander, the superheated vapor of working fluid expand to gain the mechanical work at the shaft. The scroll expander is coupled to AC-generator by belt and use some incandescent bulb as working load.

After expansion process, the low-pressure working fluid vapor flows to condenser to be cooled, water as the cooler media circulate by the cooling water pump from condenser to cooling tower which have cooling capacity 100 kW. After condensing process, the liquid working fluid gathered in liquid receiver tank to pump again to evaporator.

![Diagram of experimental set-up.](image)

3.2 The Measurement system

As shown in Figure 2, T-type thermocouples and pressure transmitters are installed at different positions in the prototype (stream 1 – 4), to measure the temperatures and pressures of the working fluid. And also the turbine flow meter used to monitor the mass flow rate of the working fluid, hot water and cooling water.
All the output signals of the experimental data can be automatically transported to the computer and recorded as functions of time in the computer, utilizing an Cole Palmer 18200-20 series data logger.

3.3 Thermodynamic Analysis of ORC System

Figure 3 illustrates the thermodynamic process for ORC system. A theoretical Rankine cycle consists of the following processes: 1 → 2: Compression (working fluid feed pump); 2 → 3: Heat supply (geothermal heat source); 3 → 4: Expansion (expander); 4 → 1: Heat rejection (condenser).

Figure 3. T-s diagram for ORC System.

The analysis of the cycle consists of applying mass and energy balances to each of the processes mentioned above. Process 1 → 1 is the work done by the working fluid pump:

\[ W_p = (h_3 - h_4)/\eta_p \]  \hspace{1cm} (1)

Process 2 → 3 is the heating process in the evaporator where geothermal heat transferred to the working fluid:

\[ Q_{evap.} = (h_4 - h_1) \]  \hspace{1cm} (2)

Process 3 → 4 is the actual expansion of the working fluid through the turbine:

\[ W = (h_1 - h_2) \eta_m \eta_s \]  \hspace{1cm} (3)

Process 4 → 1 is the condensation process which occurs within counter flow heat exchanger using cooling water at 28 °C so the heat transferred to the cooling water (heat out) is:

\[ Q_{cond.} = (h_2 - h_3) \]  \hspace{1cm} (4)

The net electrical power produced by the ORC unit is:

\[ W_{cycle} = W_{exp} - W_p - W_{p1_{(lw)}} - W_{p2_{(cw)}} \]  \hspace{1cm} (5)

The thermal efficiency of the ORC unit is:

\[ \eta_{cycle} = W_{cycle}/Q_{evap} \]  \hspace{1cm} (6)
4. Results and discussion

4.1 Measured experiment data

Base on the data from the experiment data and thermodynamic analysis, Figure 4 shows the impact of evaporator hot water inlet temperature variations from 60°C to 100°C to the cycle performance and expander power output. As the hot water inlet temperature increased, the expander power output and system efficiency also increased. This effect is the dominant effect accompanied by increasing the working fluid enthalpy mean while the work of the feed pump still remains ($\dot{m}_f$ set to be constant).

![Figure 4](image1.png)

**Figure 4.** Impact of the hot water temperature variation to expander power output and system performance

From Figure 5 can be seen that with the same heating temperature, R134a and R245fa have almost the same expander inlet temperature but R245fa have much better system efficiency.

![Figure 5](image2.png)

**Figure 5.** Impact of the hot water temperature variation to expander inlet temperature and system performance
4.2 Comparison of the Output for the Two Working Fluids

The result of the thermodynamic calculation, based on experiment measured data, shows the ORC system using R245fa as working fluid, have a better performance than R134. The highest net output is $P_{\text{out, net}} = 1,908.9$ watts with $\eta_{\text{cycle}} = 5.62\%$. The comparison of the two working fluids can be seen on Table 1.

| No | Item                                      | R-134a | R-245fa |
|----|-------------------------------------------|--------|---------|
| 1  | Temperature of hot water ($T_{\text{hw}}$ / °C) | 100    | 100     |
| 2  | Expander inlet temperature ($T_{\text{in expd}}$ / °C) | 84,45  | 84,04   |
| 3  | Expander outlet temperature ($T_{\text{out expd}}$ / °C) | 39,13  | 55,16   |
| 4  | Expander inlet pressure ($P_{\text{in expd}}$ / bar) | 26,2   | 8,6     |
| 5  | Expander outlet pressure ($P_{\text{out expd}}$ / bar) | 8      | 2       |
| 6  | System efficiency ($\eta_{\text{cycle}}$ / %) | 2,16   | 5,62    |
| 7  | Expander efficiency ($\eta_{\text{exp.}}$ / %) | 67,37  | 84,13   |
| 8  | Fluid mass flow rate ($m_f$ / kg/h) | 450    | 450     |
| 9  | Hot water mass flow rate ($m_{hw}$ / kg/h) | 2000   | 2,000   |
| 10 | Expander difference pressure ($\Delta P$ / bar) | 18,2   | 6,6     |
| 11 | Net Power / $P_{\text{out, net}}$ (watt) | 1334,7 | 1908,99 |

5. Conclusion

It has been shown in this study that it is possible to use an organic Rankine cycle to produce electrical power from a low temperature geothermal source. A comparison result between two working fluids, R-134a and R-245fa, revealed that the refrigerant R-245fa had a better performance.

Increasing the temperature of heat source will increase the power output and system efficiency. However, many tasks should be done to see the effect of changing design parameters on the net power output and total system efficiency. Plans for the future work to thoroughly analyse and describe the sensitivity analysis for total ORC.

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