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The Effect of Expander Input and Output Pressure Ratio on the Performance of Simple Organic Rankine Cycle With Low Quality Geothermal Steam as the Heat Source

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Abstract

Electricity currently plays essential role to support the lives of modern society and national development in Indonesia. The use of renewable energy resources to produce electricity need to be continually encouraged since the exploitation of fossil energy sources to generate power have been depleting the energy reserves. In addition, the use of fossil energy pollutes for the environment. For these reasons, a lot of studies need to be carried out to find out the best possibilities to generate power using renewable energy sources. In this study an experimental investigation of the performance of a small-scale power generation system using an organic Rankine Cycle (ORC) system with a low-quality geothermal steam as the heat source is carried out. The experimental system was designed, built and tested using R134a as a working fluid. This small-scale power generation unit uses key components such as a vane type pump, to increase the pressure of the working fluid, the evaporator, to absorb heat from the heat source, the expander (turbine), to expand the heat vapour to generate work on shaft, and the condenser, to change the fluid phase into saturated liquid. Some parameters such as heating steam temperature and mass flow rate of the working fluid will be varied during the experiment to obtain the best system performance. From the test results it is obtained that the highest thermal efficiency of the system is 5.34% and the net output power is 1523.42 Watt. The experimental results show that using low-quality geothermal steam in the power generation system using this ORC system is feasible to use with acceptable performance.

Keywords: renewable energy, geothermal, organic Rankine cycle

Abstrak

Listrik saat ini memiliki peran yang sangat penting dan strategis untuk mendukung kehidupan masyarakat modern dan pembangunan nasional di Indonesia. Penggunaan sumber energi terbarukan untuk menghasilkan listrik harus terus didorong, mengingat cadangan sumber energi fosil yang telah digunakan sejauh ini semakin menipis, selain itu juga tidak ramah terhadap lingkungan. Oleh sebab itu banyak penelitian perlu dilakukan untuk menguasai teknologi penggunaan sumber energi terbarukan ini sehingga dapat dikonversi menjadi energi listrik. Dalam studi ini analisis eksperimental dilakukan terhadap kinerja sistem pembangkit listrik skala kecil menggunakan sistem Siklus Rankine Organik sederhana dengan sumber panas geothermal berkualitas rendah. Sistem eksperimental dirancang, dibangun dan diuji menggunakan R134a sebagai fluida kerja. Unit pembangkit listrik skala kecil ini menggunakan komponen kunci seperti vane pump, untuk meningkatkan tekanan fluida kerja, evaporator, untuk menyerap panas dari sumber panas, expander (turbin), untuk mengubah panas menjadi energi kinetik yang kemudian diubah menjadi kerja poros, dan kondensor, untuk mengubah kerja fase fluida kembali menjadi cairan jenuh. Beberapa parameter seperti temperatur uap panas dan laju aliran massa fluida kerja akan bervariasi selama percobaan untuk mendapatkan kinerja sistem terbaik. Dari hasil pengujian diperoleh efisiensi termal tertinggi dari sistem adalah 5,34% dan daya keluaran bersih adalah 1.523,42 watt. Hasil percobaan menunjukkan bahwa penggunaan uap panas bumi berkualitas rendah dalam sistem pembangkit listrik menggunakan sistem Siklus Rankine Organik ini layak untuk digunakan dengan kinerja yang dapat diterima.

Kata kunci: energy terbarukan, geothermal, siklus organic Rankine

1. Introduction

The consumption of fossil fuels for power generation creates many environmental problems such as global warming, ozone depletion and atmospheric pollution. However, fossil fuels still play a dominant role as energy resources to generate electricity as the energy demands keep raising. Therefore there is an urgent necessity to produce power from natural or waste low-grade heat sources such as solar thermal, biomass, geothermal and industrial waste heat.

Indonesia has a great deal of potential natural heat sources that can be developed into electrical energy, such as solar and geothermal energy. Among these various heat sources, a low temperature heat source from geothermal attracts great interest to be developed as a solution to fulfil the energy needs in remote areas having respective heat source.

Organic Rankine cycle (ORC) is a promising power generating cycle for energy conversion from low-temperature heat sources. U.S. Department of Energy (U.S. DOE) indicated that approximately 60% of low-temperature waste heat (below 232 °C) is not recovered and this heat is in large quantities [1]. 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 absorb the heat, turbine (or expander), to convert the heat energy contained in the working fluid to the power of a shaft and condenser, to remove the heat from the working fluid. The major difference is the choice of the working fluid, ORC uses organic component instead of water.

In order to convert low-temperature heat sources to useful work, Yamamoto et al. experimentally demonstrated that the use of a low boiling point working fluid, such as R-123, in the Rankine cycle resulted in a better cycle performance compared to application of water for the turbine inlet temperature below 120 °C [2]. For this reason, the ORC systems have been widely investigated for various applications.

Lakew and Bolland analysed 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, determined the heat source temperature from 80°C to 200°C and considered the evaporator pressure as independent parameter. The results show that the choice of working fluids is determined by the type of the heat source, the temperature level and the design goal. The key goal is obtain the possible highest power of the turbine or lesser dimensions of the components. It is stated that the most power generated is reached at 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 [4]. Qiu et al. gave an overview of the 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 [2].

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 steam as the heat energy source into a shaft power, and the system utilized R134a as the working fluid.

2. Material and Method

2.1. System Description

The designed Organic Rankine Cycle (ORC) system consists of three loops, as can be seen in Figure 1. The first loop is the refrigerant loop. In this loop, the liquid refrigerant, acting as a working fluid (R134a or R245fa), is pressurized by the feed pump. The pressurized liquid is than heated in the tubing of the evaporator by the hot water flowing in the evaporator shell until its phase changes to saturated vapour. The fluid leaves the evaporator in dry saturated condition and enters the modified scroll compressor, operating as an expansion device. The expansion process driven by an electrical generator produces electric power. After leaving the expander, the working fluid enters the condenser and is cooled by the cooling water until it turns to saturated liquid. Afterwards it is pumped again to the evaporator. The second loop demonstrates the heat source loop. Here the hot water from the water boiler (simulating of low-temperature hydrothermal heat source) streams to the evaporator. The third loop reveals the cooling water loop. In this cycle the cooling water circulates to absorb the heat from the working fluid in condenser and subsequently rejects the heat to the cooling tower.

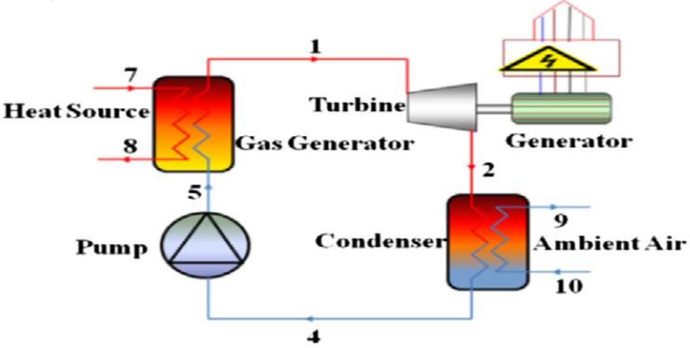

Figure 1. Schematic diagram of ORC System.

2.2. Experimentas Set-up

A small-scale ORC power generating was designed, constructed and tested based on the required condition. Figure 2 shows the schematic diagram of the experimental system. The experimental prototype consists of an evaporator, a water boiler, a gas tank, an expander, a throttling valve, a condenser, a liquid tank, a 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 a maximum operating pressure of 28 bars and a rotational speed of 1200 rpm. The working fluid mass flow rate is defined at 450 kg/h for all level of heating temperature. To simulate the hydrothermal heat source, a water boiler is used. The hot water from the water boiler is supplied to heat up the working fluid in the evaporator coil pipes using a hot water pump with constant mass flow rate of 2000 kg/h and temperature varying between 60 °C to 100 °C. After the heating process in the evaporator, the superheated working fluid vapour is afterwards collected temporarily in the gas tank whose volume is 10 litres and the allowable working pressure is 30 bars. The use of a gas tank creates a more stable expander inlet pressure. In the expander the superheated vapour of the working fluid expands to gain the mechanical work at the shaft. The scroll expander is coupled to AC-generator by belt and uses some incandescent bulb as the working load.

After expansion process, the low-pressure working fluid vapour flows to the condenser to be cooled and the water, the cooler media, is circulated by the cooling water pump from condenser to cooling tower with cooling capacity of 100 kW. After the condensing process the working fluid collected in the liquid receiver tank is finally flowed to evaporator.

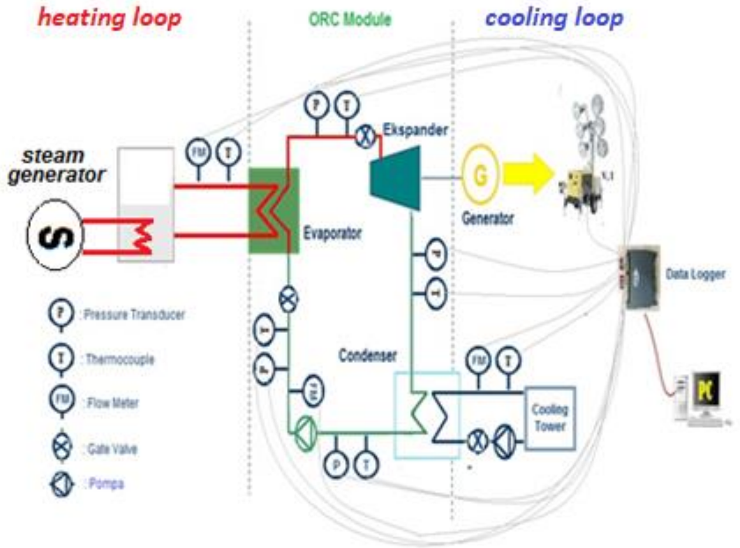

Figure 2. Diagram of experimental set-up.

2.3. The Measurement System

As can be seen 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. A turbine flow meter is 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, using a Cole Palmer 18200-20 series data logger.

2.4. Thermodynamic analysis of ORC system

Figure 3 illustrates the thermodynamic process of an ORC system. A theoretical Rankine cycle consists of the following processes: 1→2: Compression; 2→3: Heat supply; 3→4: Expansion; 4→1: Heat rejection.

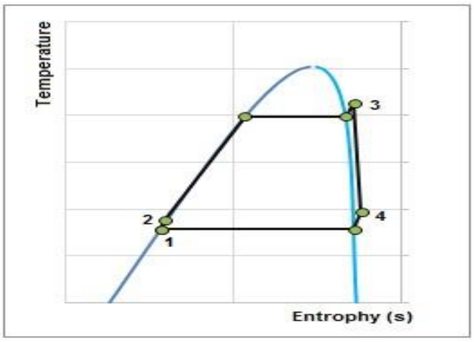

Figure 3. T-s diagram for ORC System.

The analysis of the cycle consists of applying mass and energy balances to each of the processes mentioned above. Process 1 → 2 is the work done by the working fluid pump:

$$W_p = (h_2 - h_1)/\eta_p \tag{1}$$

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

$$Q_{evap} = (h_3 - h_2) \tag{2}$$

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

$$W = (h_3 - h_4).\eta_m.\eta_s \tag{3}$$

Process 4 → 1 is the condensation process taking place in the counter flow heat exchanger using cooling water at 28°C. Therefore, the heat transferred to the cooling water (heat out) is:

$$Q_{cond.} = (h_4 - h_1) \tag{4}$$

The net electrical power produced by the ORC unit is:

$$\mathrm{W_{cycle} = W_{exp} - W_p - W_{p1_{(hw)}} - W_{p2_{(cw)}}} \tag{5}$$

The thermal efficiency of the ORC unit is:

$$\eta_{\mathrm{cycle}} = \mathrm{W_{cycle}}/\mathrm{Q_{evap}} \tag{6}$$

3. Result and Discussion

3.1. Measured Experiment Data

Based on the experiment data and thermodynamic analysis, Figure 4 shows the impact of the steam temperature change at evaporator, varying from 80°C to 100°C, to the expander power output which implies to the cycle performance. As the inlet steam temperature surges, the expander power output also rises which means the increase of the system efficiency. This effect is dominant accompanied by the increasing of the working fluid enthalpy meanwhile the work of the feed pump still remains the same ($\dot{m}_f$ is set to be constant).

The simulation results show that at a constant heat source temperature, the thermal efficiency increases with lower heat sink temperature for both systems with and without recuperator. This can be explained that the lower heat sink temperature lifts up the expander pressure ratio and thus power output requires less work fluid mass flow rate if the power output is fixed. The smaller working fluid mass flow rate indicates that a smaller amount of heat source heat input is required and therefore higher thermal efficiency can be achieved. Simultaneously, at a constant heat sink temperature, the thermal efficiency improves with higher heat source temperature. At a constant evaporator pressure (14 bars), the variations of thermal efficiencies with heat source and sink temperatures for the R134a ORC systems with and without recuperator are also simulated and depicted in Figure 4. In figure 5 it can be seen the effect of R134a pressure at expander inlet. At a constant R134a pressure, the thermal efficiency enlarges with enhanced heat source temperature for the system with recuperator.

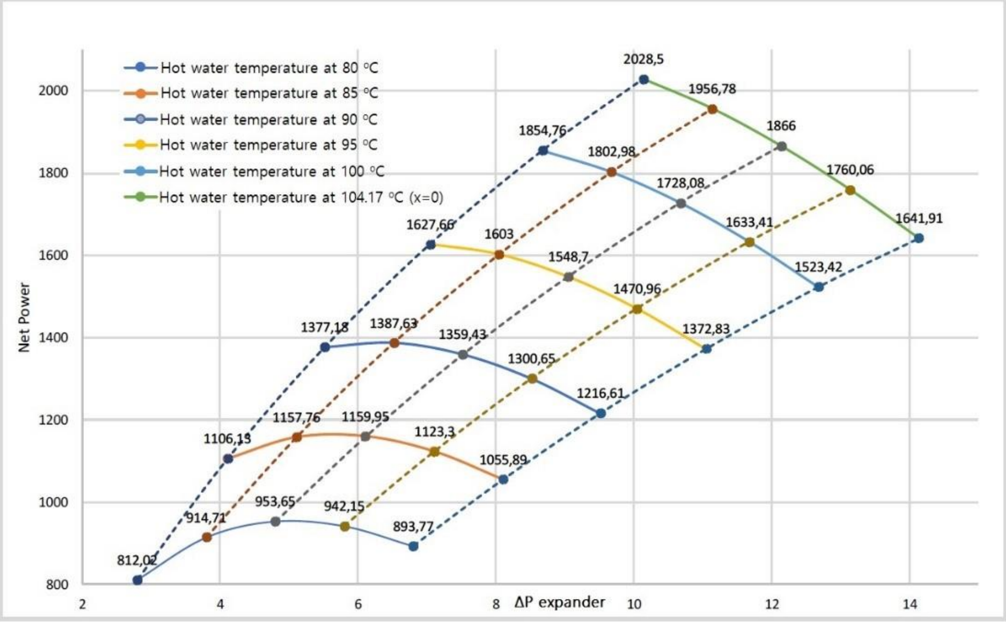

Figure 4. Effect of pressure ratio changes at expander inlet and outlet side at various steam heating temperatures at the evaporator to the system's net output Power.

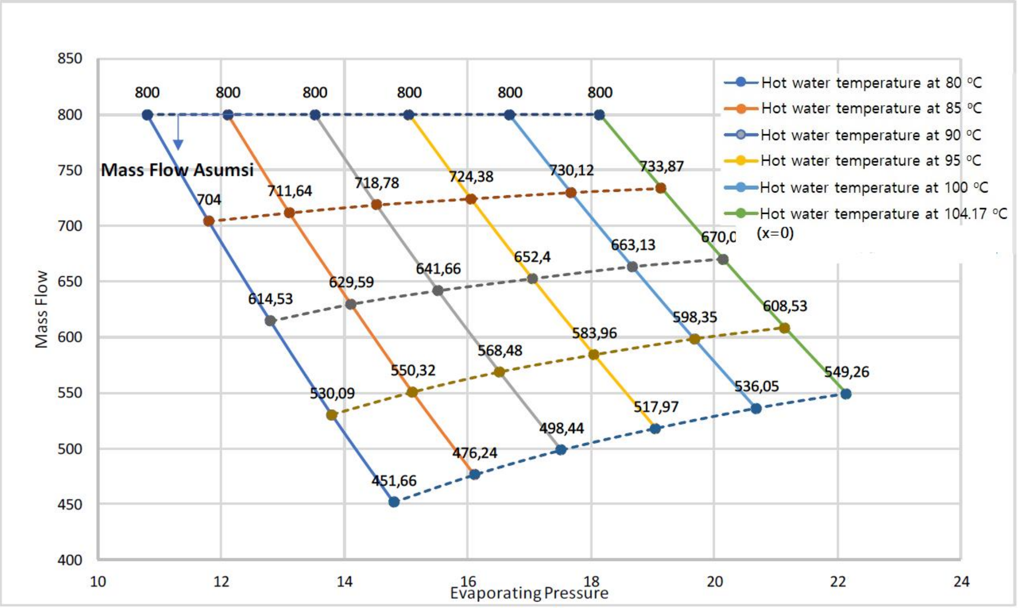

Figure 5. Effect of hot water temperature to maximum evaporating pressure & maximum mass flow.

Figure 6 demonstrates that when the cycle is operated at the higher pressure difference, the system generates predominant performance as the scroll expander with bigger built-in volume ratio is utilized. The reason behind this result is that the expander used in the present study is inadequate to operate at a pressure difference of 5 bars in the system because the output power of the expander is reduced to a prohibited value. Based on the integrated experimental data, the expander used in the present study operates best at the pressure difference higher than 6 bars.

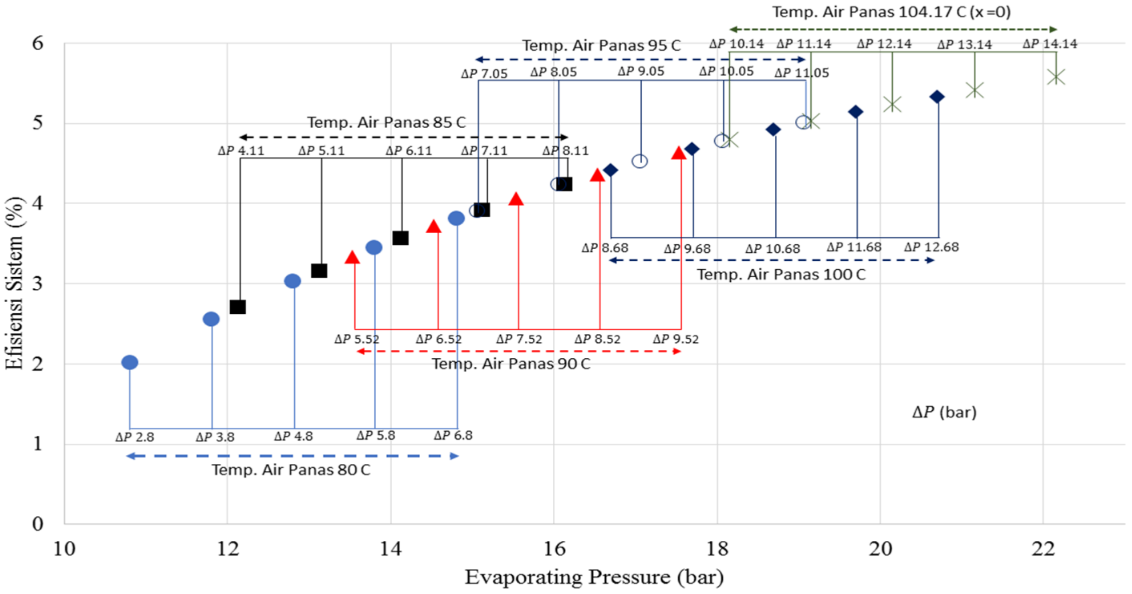

Figure 6. Effect of evaporation pressure to cycle efficiency.

4. Conclusion

This study experimentally investigates the performance of a scroll expander with a built-in volume ratio of 4.05 in an ORC system using HFC-245fa as working fluid, and the fluid has been mixed with moderate refrigerant oil that circulated in the system. The expander was modified from an oil-free open-drive scroll type air compressor and operated in reverse mode. The hot water at a pressure of one atmosphere was used as a dummy waste heat source and a cooling tower served as a heat sink. The main findings are as follows:

1. As the cycle is operated in fixed superheating of 3 ± 1 K, the maximum cycle efficiency is 5.34% at a rotational speed of1535 ± 40 RPM and a cycle pressure difference of 8 bars. The maximum power of the expander is 1.523 kW at a rotational speed of 2970 ± 50 RPM with operating cycle pressure difference at 8 bars.

2. The maximum power produced by the expander is not corresponding to the maximum cycle efficiency for the real cycle. The compromise operating conditions have relation with system pressure difference and rotational speed of the expander.
3. Both efficiencies of the expander and the cycle improve with the increasing of superheating, but the irreversibility of the evaporator also rises simultaneously.

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