Evaluation of working fluids for organic Rankine cycle power plant with Aspen plus

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Abstract. Power generation using Organic Rankine Cycle (ORC) was studied in this paper. A thermodynamic model was achieved in Aspen Plus environment and the highest output power and efficiency were obtained for on variance working fluids. The Organic Rankine Cycle (ORC) is analysed using commonly used working fluids for cycle use, they are R245fa (1,1,1,3,3-Pentafluoropropane), R11 (Trichlorofluoromethane), and R123 (2,2-Dichloro-1,1,1-trifluoroethane). The results show that some of the effects of the pressure on the inlet turbine, and working fluids variances on the performance of the cycle. The output power turbine and efficiency of the system were simulated and discussed.

1. Introduction

With such a rapid consumption of fossil fuel across the world, there are still many people unable to assess electricity. Furthermore, the conventional procedure of energy production which comes from burning fossil fuels has unwanted effects on environment such as greenhouse gas emission, air pollution, water, and soil contamination. If fossil fuel consumption will continue to be carried out, the ozone layer depletion will also occur, it will increase the global warming effect on the world. Thus, there is need of safe, sustainable and environmental-friendly source of power production. Proper utilization of renewable energy like wind, solar, geothermal and biomass are capable to decreasing the rate consumption of fossil fuel and also help to reduce the global warming and ozone depletion [1,2]. Some of verities of thermodynamic cycles such as internal combustion engine and eksternal combustion engines like organic Rankine cycle, Goswami cycle, and Kalina cycle have been successfully conversion of various heat sources into electricity [3].

The organic Rankine cycle (ORC) is considered to be an efficient and effective power generation technology, compared with other methods because of its advantages in thermal efficiency, variable load adaptability, low cost, and operational maintenance. Convert low-grade thermal energy into useful mechanical, and thus in electric energy, is called Organic Rankine Cycle (ORC), and consists of the use of organic fluids with a high molecular weight in the Rankine cycle. The temperature of the liquid-vapor phase change of these fluids is lower than the water cycle one. This feature permits to produce electric energy also from low-medium temperature heat sources. Furthermore, many studies have been devoted to analyze the performance of organic Rankine cycle. Talieh [5] studied effect of low temperature using Organic Rankine Cycle for power generation and observed effect of different cold load on cycle. Anastasios and Nikolaos [6], investigated and evaluated the potential of electricity generation using medium temperature geothermal resources in Northern Greece. In this paper showed that ORC could produce electricity power or about 2 MW in expected. Joraslaw and Janusz [7] compare the performance...
of ORC and Kalina cycle for waste heat recovery in the steel industry. The efficiency of system for ORC was higher than KC. Matew et al. [8] analysis the effect of geothermal temperature source on plant performance. The analysis had shown that increase in the source temperature will increase the plant output power up to a certain limit; however, this occurs at the detriment of the plant thermal efficiency which decreases. Arun Kumar and Shukla [9] analysis performance of ORC using benzene as a working fluid. The efficiency of ORC system has been varied with possible temperature of turbine outlet as well as with mass flow rate at the inlet of turbine.

The selection of a potential working fluid is one of the important factors in organic Rankine Cycle (ORC) system. The working fluids affects the thermodynamic design and performance of all components within the system. For this research, focus to study to obtain the maximum cycle efficiency of organic Rankine cycle. The working fluid of system which is considered in this study are R245fa, R11, and R123 for the organic Rankin cycle. The organic Rankin cycle process was simulated using Aspen plus V10.

2. Thermodynamic modelling

The principal processes of the organic Rankine cycle system are illustrated in figure 1 which shows the temperature-entropy diagram of the thermodynamic cycle. The second law of thermodynamics, conservation of energy, conservation of mass, and thermodynamic parameter are part of the thermodynamic analysis. The common component of the ORC plant should consist of pumps, evaporator, scroll expander, and the condenser. By observing their pressure and temperature on each individual component in the organic Rankine cycle system to evaluate the thermodynamic properties of working fluids.

![Figure 1. The principle operation of the organic Rankine cycle (ORC) system.](image)

The mathematical model of each individual component is calculated as follows:

2.1 Input Power Pump

The input power pump increases working fluid pressure from state 1 to state 2 in order to match the operation rate of the evaporator. Volume control was built around the pump as a barrier for incoming and outgoing heat transfers with the surrounding. The pump power can be written as:

$$ W_p = \dot{m} (h_2 - h_1) $$

(1)

where $\dot{m}$ represents mass flow rate for working fluid. Isentropic efficiency ($\eta_{is,\text{pump}}$) and mechanical efficiency ($\eta_{me,\text{pump}}$) can be expressed as:
where \( h_{2s} \) and \( h_2 \) are the specific enthalpies of the working fluid at the outlet of the pump under ideal and actual conditions, respectively.

2.2 Evaporation Process
The compression vapour flows throughout an evaporator at state 3. The total heat transfer rate \((Q_{\text{evp}})\) from the heat source to working fluid in the evaporator is represented in:

\[
Q_{\text{evp}} = m(h_3 - h_2)
\]

where \( h_3 \) is the specific enthalpy of working fluid at the evaporator outlet.

2.3 Expansion work of scroll expander
The superheated vapour at state 3 flows in scroll expander where it expands and produces output power by rotating the shaft. The pressure and temperature drop during this process then discharge to state 4. By neglecting heat transfer flow in and flow out to the surrounding, the scroll expander output power \((W_t)\) can be written as:

\[
W_t = m(h_3 - h_4)
\]

where \( h_4 \) is the specific enthalpy of working fluid at the expander outlet.

2.4 Condensation process
A condenser facilitates heat transfer from steam to cooling water that flows in a separate channel. According to the principle of mass and energy balance for a controlled volume at a condenser, the output heat can be written as:

\[
Q_{\text{cond}} = m(h_4 - h_3)
\]

where \( Q_{\text{cond}} \) is the condenser output heat and \( h_4 \) is the specific enthalpy of working fluid at the condenser inlet.

2.5 Thermal efficiency
The thermal efficiency can be represented as the ratio between total output to input powers and heat transfer rate. The thermal efficiency can be described as:

\[
\eta_{th} = \frac{W_t - W_p}{Q_{\text{in}}} = \frac{(h_3 - h_4) - (h_2 - h_1)}{(h_4 - h_3)}
\]

Since work input and output powers are equal to total operating heat, another expression of the thermal efficiency may be calculated as follows:

\[
\eta_{th} = \frac{Q_{\text{in}} - Q_{\text{out}}}{Q_{\text{in}}} = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}} = 1 - \frac{(h_4 - h_3)}{(h_3 - h_2)}
\]

3. Simulation model
The modelling and simulation for this work was implemented using the Aspen Plus software. Aspen Plus is process flowsheet simulator, it provides for calculation of the thermodynamic properties. It also provides built-in blocks simulating the basic processes such as pressure chargers, heat exchanger and expander required for the modelling of the cycles. In the following sections the modelling methodology of each component of the systems is described using the Aspen Plus terminology. The turbine and pump
are simulated in Aspen Plus using the Compr in Pressure changer defining the exit pressure and isentropic efficiencies. The evaporator, and the condenser are simulated using the HeatX block in heat exchanger with a shortcut calculation method selected. In the condenser, it is required that the vapour fraction at the exit is zero. Two more parameters are set: the temperature inlet geothermal in the evaporator and the water cold inlet temperature in the condenser. Figure 2 shows the organic Rankine cycle model developed in Aspen Plus.

| Table 1. Initial parameter as working fluids for simulation of present ORC system |
| ASHRAE Number | Working fluids (Chemical formula and name) |
|----------------|--------------------------------------------|
| R245fa         | CHF₂CH₂CF₃ (1,1,1,3,3-Pentafluoropropane)   |
| R11            | CCl₃F (Trichlorofluoromethane)              |
| R123           | C₃HCl₃F₃ (2,2-Dichloro-1,1,1-trifluoroethane) |

The main operational conditions and assumption for plant calculation as described in table 2.

| Table 2. Assumed parameter used for cycle simulation model |
| Parameter                              | Value     |
|----------------------------------------|-----------|
| Mass flow rate of working fluid (kg/hr)| 3600      |
| Phase fraction of working fluid (outlet of pump) | 0         |
| Phase fraction of working fluid (outlet of heat exchanger, outlet expander) | 1         |
| Outlet pressure of expander (bar)      | 2         |
| Geothermal fluid mass flow rate (kg/h) | 40000     |
| Geothermal fluid temperature (°C)      | 100       |
| Cooling water mass flow rate (kg/hr)   | 30000     |
| Cooling water source temperature (°C)  | 27        |
| Efficiency turbin (%)                 | 80        |
| Efficiency Pump (%)                   | 80        |
4. Result and discussion
Three ORC systems were analysed, with R245fa (1,1,1,3,3-Pentafluoropropane), R11 (Trichlorofluoromethane) and R123 (2,2-Dichloro-1,1,1-trifluoroethane) as working fluids to obtain the highest electricity output by varying the turbine inlet pressure, and obtain the effects of working fluid and operating conditions on efficiency are analyzed. During the simulation, pressure outlet turbine ($P_{out}$) of the ORC is set to 2 bar and the pressure inlet turbine ($P_{in}$) changes are 3 to 6 bar with an interval 1 bar. As simulated pressure and temperature geothermal resources were constant (100°C) as temperature and pressure of water cold in condenser (27 °C). The mass flow rate of the system was constant at 3600 kg/hr. From simulation showed that pressure inlet turbine and working fluids variance has effect for performance of organic Rankine cycle.

Figure 3 shows changes in the system performance under different pressure inlet turbine ORC. The pressure working fluid of the heat source has a nominal value and equals to 3 bar. For each pressure, the system was optimized for the maximum system efficiency. With the increase of pressure in the range from 3 to 6 bar, the power output ORC of the system goes up from 4 kW to 12 kW with three fluid workings of the cycle demonstrate low pressure to higher. Figure 4 shows changes in the efficiency system under different pressure inlet turbine ORC The efficiency of the system goes up from 2% to 6%.

**Figure 2.** Flowsheet of the Aspen Plus ORC model
Figure 3. Outlet power of ORC turbine for variance working fluids

From figure 3 shows outlet power of ORC turbine for variance working fluids, The highest outlet power was obtained for R11 (Trichlorofluoromethane) as working fluid. The differences in power and output power between R11 and R245fa do not exceed 2% and the differences power in and power output turbine between R11 and R123 was 9%. The figure showed that increase the pressure inlet turbine has increase the outlet power turbine ORC.

Figure 4. Efficiency of ORC turbine for variance working fluids

From figure 4 shows the variation in working fluid at Organic Rankine Cycle, The highest efficiency was obtained for R11 (Trichlorofluoromethane) as working fluid. The highest efficiency value (6.58%) was obtained for R11 (Trichlorofluoromethane) as working fluid with pressure inlet turbine 6 bar, and ORC based on R245fa (1,1,1,3,3-Pentafluoropropane) has lower efficiency. The simulated shown that increase in the pressure inlet turbine will increase the efficiency the system ORC.
5. Conclusion
The ORC to generated the electricity was simulated and analysed in this study. Aspen Plus V10 software simulation was used to calculate the thermodynamic characteristics of the design. The result of this study showed that the highest electricity output power turbine was obtained for R11 (Trichlorofluoromethane) as the working fluid and the highest efficiency system of ORC was obtained for R11 (Trichlorofluoromethane) as working fluid. The simulated shown that an increase in the pressure inlet turbine will increase the efficiency of the system ORC. Utilized working fluid base on R11 is better than R245fa and R123 due R11 has the highest efficiency and electricity power output turbine.

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