Investigation of exergy efficiency of organic Rankine cycle

G L Liu1,3, J L Xu1 and S Cao2
1Beijing Key Laboratory of Multiphase Flow and Heat Transfer for Low Grade Energy Utilization, North China Electric Power University, Beijing, 102206, Beijing, China
2School of Energy and Power Engineering, Zhengzhou University of Light Industry, Zhengzhou 450002, Henan Province, China
E-mail: liu0513@126.com

Abstract. Organic Rankine cycle (ORC) which recovers waste heat in the temperature range of 80°C-140°C was investigated. Exergy efficiencies of various components and ORC system were paid great attention. The working fluids of R245fa and R600a are used. It is found that, for saturated ORCs, the expander inlet temperature has the optimum value, so the system exergy efficiency is maximum. With the increase of heat source temperature, the optimal inlet temperature of the expander is also increased. And also for saturated ORCs, the exergy efficiencies of evaporator and expander are highest efficiency, when evaporator exergy efficiency is increased with increase of heat source temperatures, the expander exergy efficiency is unchanged. The condenser decreased exergy efficiencies by increasing the heat source temperatures.

1. Introduction
Electricity is the core energy for social development. With the increasing prominence of fossil energy consumption and environmental problems, more and more researchers have studied the use of renewable energy for power generation. Organic Rankine cycle power generation system is one of effective using ways for low grade energy.

Many scholars had studied the optimization of the system, the working fluid and the main equipment. The key parameters of organic Rankine cycle had been studied by experience using high-temperature and low-temperature for heat source, the system stability and working fluids were also observed [1]. Pressure and flow rate as two important participants to optimize for subcritical and transcritical system, and 36 refrigerants had been compared [2]. Screw expander and R218 working fluid investigated for supercritical organic Rankine cycle using 90-100°C heat source [3]. Micro axial and radial-inflow turbines as a key research object for organic Rankine cycle had been investigated for improve the system efficiency, the scale of expander has lowest scale if R245fa as the working fluid and thermal efficiency is more than 10% [4].

Exergy analysis using for the ORC cycle coupled to IC engine, it could be improvement highly for this type of cycles and the expander has bigger potential than other components under the conditions of endogenous and exogenous [5]. Exergy, exergoeconomic and exergoenvironmental are all considering for the ORC system and in order to get multi-objective optimization operating conditions [6]. Energy and exergy efficiencies analysis evaporator, condenser, turbine, and regenerator for the biomass-based plant using two Case date, which could list exergy destructions of the components [7]. Exergy analysis inlet pressure, heat source temperatures and working fluids for coupled transcritical
and subcritical organic Rankine cycle driven by the waste heat of the flue gas. Exergy loss is mainly focus on heat exchangers and expanders [8].

The investigation of system optimization is mainly based on the first law of thermodynamics. This paper uses the exergy analysis method to study the system and the main components of Organic Rankine cycle power generation system.

2. Organic rankine cycle power system model

The basic organic Rankine cycle power generation system schematic diagram is shown in figure 1. The working principle of power system: liquid working fluids in the evaporation heat exchanger is heated to saturation state then entering expander for pushing expander to output work, working fluids from the expansion and then enters the condenser to be condensed into liquid state, and liquid working fluids through a pump for pressurized again into the evaporation for heat exchanger. Heat source enters the evaporation to heat exchanger with working fluids, and the liquid working fluids are heated into gas and heat source temperature decreasing. The whole cycle power generation system is mainly composed of expander, evaporator, condenser and working fluid pump.

In this paper, exergy efficiency is taken as the evaluation for analyze the efficiency of the system and the main equipment under different conditions. For the basic organic Rankine cycle power generation system, the exergy efficiency of the system can be formula as:

$$\eta = \frac{W_{net}}{m_g \cdot [(h_5 - h_0) - T_0 \cdot (s_5 - s_0)]}$$  \hspace{1cm} (1)

In equation (1), $W_{net}$ is the effective use of exergy, and equal the system net output work, kW. The net power output equal the expansion out power subtract pump consumption, the formula as:

$$W_{net} = W_{ep} - W_{cp}$$  \hspace{1cm} (2)

$W_{ep}$ is expander output power, $W_{cp}$ is the pump consumption work, as follows:

$$W_{cp} = m_{of} \cdot (h_1 - h_2)$$  \hspace{1cm} (3)

$$W_{cp} = m_{of} \cdot v_3 \cdot \frac{(p_1 - p_2)}{\eta_p}$$  \hspace{1cm} (4)

Evaporator exergy efficiency formula as:
\[\eta_c = \frac{m_{wf} \cdot [h_1 - h_4 - T_0 \cdot (s_1 - s_4)]}{m_g \cdot [h_3 - h_6 - T_0 \cdot (s_3 - s_6)]}\]  

(5)

Condenser exergy efficiency formula as:

\[\eta_c = \frac{m_{cw} \cdot [h_7 - h_k - T_0 \cdot (s_7 - s_k)]}{m_{wf} \cdot [h_2 - h_3 - T_0 \cdot (s_2 - s_3)]}\]  

(6)

Expander exergy efficiency formula as:

\[\eta_{ep} = \frac{W_{ep}}{m_{wf} \cdot [(h_1 - h_2) - T_0 \cdot (s_1 - s_2)]}\]  

(7)

In equations (1)–(7), \(m_{wf}\), \(m_{cw}\), \(m_g\) are mass flow of working fluids, cooling water and heat fluid [kg/s]; \(T_x\) is the temperature corresponding position in figure 1, [°C]; \(h_x\) is the enthalpy corresponding position in figure 1, [kJ/kg]; \(s_x\) is the entropy corresponding position in figure 1, [kJ/kg·K], \(\eta_p\) is efficiency of the working fluid pump, 80%; \(p_1\), \(p_2\) and \(v_3\) are the working fluid pressure and volume quality corresponding to the points in figure 1. There is a minimum temperature difference between heat source temperature and organic working fluid in the evaporator heat transfer, known as the hint temperature, which is usually between 3-7°C, and in this paper the hint temperature is 5°C. Mass flow of heat source is 1 kg/s, expander efficiency is 80%, \(T_0\) is the ambient temperature, 293 K. Considering the working fluid physical properties, such as the destruction of the ozone layer, the greenhouse effect, flammability, toxicity, R245fa and R600a working fluid are selected to simulation. Assuming no pressure loss in the equipment and piping system, ignoring other factors.

3. Model simulation and analysis results

![Figure 2. System exergy efficiency versus expander inlet temperature.](image)

R600a, R245fa, R600 are used for stimulate the system exergy efficiency versus expander inlet temperature for saturated organic Rankine cycle at the condition of constants of heat source and cold source temperature. Then analyses the major components exergy efficiency with different heat source temperature. As shown in figure 2, system exergy efficiency has the maximum value with the expansion inlet temperature increasing; the maximum system exergy efficiency is 35% using R600a as working fluid. From formula 1, it can be seen that the system exergy efficiency is influence by output net power when the heat source temperature and mass flow are constant, formula 2 shows output net
power equal expansion output power minus working fluid pump consumption. When the expander inlet temperature becomes larger, the expander output power increases first and then decreases, but the working fluid pump consumption unchanged, so result in system exergy efficiency has maximum value.

Analysis the system exergy efficiency and main equipment exergy efficiency when the heat source temperature is changing from 80°C-140°C and the other parameters are constant. Because the exergy efficiency of the expander and the working fluid pump is basically unchanged, so exergy efficiency of the expander, evaporator and condenser are paid great attention. Figure 3 shows the relationship between the system exergy efficiency versus heat source temperature. Figure 4 shows the relationship between the evaporator and condenser exergy efficiency versus heat source temperature. As can be seen from the diagram, the exergy efficiency of the system and evaporator increases with the increase of the heat source temperature. The change trend of condenser efficiency is opposite, mainly due to the increase of the heat source temperature resulting in the expansion outlet temperature of working fluid go up, so the condenser exergy efficiency is reducing.

![Figure 3. System exergy efficiency versus heat source temperature.](image1)

![Figure 4. Condense and evaporator exergy efficiency versus heat source temperature.](image2)

4. **Conclusions**

In this paper, Organic Rankine cycle (ORC) which recovers waste low heat in the temperature range of 80°C -140°C was investigated. Exergy efficiencies of various components and ORC system were paid great attention. The working fluids of R245fa and R600a are used. It is found that, for saturated ORCs, the expander inlet temperature has the optimum value, so the system exergy efficiency is maximum. With the increase of heat source temperature, the optimal inlet temperature of the expander is also increased. And also for saturated ORCs, the exergy efficiencies of evaporator and expander have highest efficiency, when evaporator exergy efficiency is increased with increase of heat source temperatures, the expander exergy efficiency is unchanged. The condenser decreased exergy efficiencies by increasing the heat source temperatures.

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