Study on The Two Level of Organic Rankine Cycle Applied to Mine Vehicle Exhaust Heat Recovery System

Wei Li, Zhibin Li, Kongbo Wang and Sa Xiao

ABSTRACT

The thermodynamic system model is established in this study. Using R123 as refrigerant, in different refrigerant evaporation temperature and expansion ratio under the condition of thermal performance of two organic Rankine cycle system and ordinary organic Rankine cycle system is analyzed in the paper. The research shows that the two level of organic Rankine cycle system has obvious advantages of high heat utilization rate and the better heat recovery effect.

KEYWORDS

Engine, Organic Rankine Cycle, Waste Heat Recovery

INTRODUCTION

With the development of industry, the demand for mining vehicles is more and more, and the consumption of fuel is also increasing. The problem of energy consumption has long been one of the urgent problems that industrial development needs to solve. The development of vehicle waste heat utilization technology has improved the utilization rate of energy, and provided an effective way to solve the problem of energy consumption of mining vehicles. Organic Rankine cycle using...
low boiling point organic refrigerants, applied to low quality waste heat recovery. By theoretical analysis and practical application prove that the organic Rankine cycle has a great potential value in improving the utilization rate of energy research[1]

Figure 1. The common organic Rankine cycle system.  Figure 2. Two organic Rankine cycle system.

ORGANIC RANKINE CYCLE SYSTEM

The system is shown in figure 1. The ordinary Rankine cycle system is mainly composed of evaporator, condenser and expansion machine, refrigerant pump[2]. As shown in figure 2. The exhaust steam flowing enters the regenerator from the single screw expander I. The refrigerant is heated again in the regenerator, and then enter the single screw expander II to do work once more. The subsequent cycle process is the same as that of the conventional circulatory system. Meanwhile, in the case of the above basic selection principle[3~5], R123 is chosen as the medium used in the study.

THE THERMODYNAMIC MODEL OF ORGANIC RANKINE CYCLE SYSTEM

Figure 3. The common organic Rankine T~S.  Figure 4. Two organic Rankine T~S.
The ordinary Rankine cycle system T-S diagram is shown in Figure 3; the two stage cycle system is shown in Figure 4. Theoretical cycle analysis and the state of Rankine cycle in the process of change as shown in Figures 3 and 4. The \( m_p \) and \( m_g \) respectively represent the engine exhaust mass flow, refrigerant mass flow, unit kg/s. \( c_p \) is the specific heat capacity at constant pressure. \( t_{w1}, t_{w2} \) represent the inlet and outlet temperature of evaporator. \( h_1 \) actual representative specific enthalpy of each state point of a refrigerant, unit kJ/kg.

1) Isobaric absorption. Ignoring heat loss, the heat absorption of organic working medium is equal to the exhaust heat.

Ordinary circulating heat: 
\[
Q_1 = c_p m_p (t_{w1} - t_{w2}) = m_g (h_1 - h_4) \tag{1}
\]

Two stage circulating heat: 
\[
Q'_1 = c_p m_p (t_{w1} - t_{w2}) = m_g (h_1 - h_6) \tag{2}
\]

2) Actual expansion process. Ordinary cycle: The isentropic efficiency of single screw expander is

\[
\eta_s = \frac{h_1 - h_2}{h_1 - h_{2s}} \tag{3}
\]

Two stage cycle: The isentropic efficiency of single screw expander is

\[
\eta_s' = \frac{h_1 - h_2}{h_1 - h_{2s}} \tag{4}
\]

\( h_{2s} \) is the theoretical enthalpy of the exit of single screw expander. \( \eta_m, \eta_m', \eta_m'' \) represent respectively the mechanical efficiency of the conventional and two stage single screw expander. For the two stage cycle, after completing the first stage expansion, the working substance enters the regenerator and heats again, and then enters the II expansion machine to do expansion work. In this process, heat absorption and work are as follows:

Reheat heat absorption:
\[
Q_2 = c_p m_p (t_{w2} - t_{w3}) = m_g (h_3 - h_2) \tag{5}
\]

The actual expansion process of superheated steam in a single screw expander II:

\[
\eta_s'' = \frac{h_3 - h_4}{h_3 - h_{4s}} \tag{6}
\]

3) Isobaric condensation process

Ignoring condenser heat loss, The organic working medium releases heat equal to the amount of heat absorbed by the cooling water.
Ordinary cycle:  \[ Q_2 = m_g (h_2 - h_3) \]  
(7)

Two stage cycle:  \[ Q_n = m_g (h_4 - h_5) \]  
(8)

4) Isentropic compression process
   Ordinary cycle: The power consumption of the refrigerant pump is
   \[ W_b = m_g (h_4 - h_3) / \eta_b \]  
(9)

   \( \eta_b \) is working fluid pump mechanical efficiency.
   The power consumption of the two stage circulating refrigerant pump is
   \[ W_b' = m_g (h_6 - h_5) / \eta'_b \]  
(14)

CALCULATION RESULTS AND ANALYSIS

Conditions Of Circulating Medium

The diesel engine of a certain mining vehicle is selected as the object of study. The working point at the big torque of the diesel engine and the maximum heat of the exhaust gas is selected as the working point. Table 1 is the test data of the selected working conditions. Set two systems, running the same basic conditions: ambient temperature 298K, the isentropic efficiency of single screw expander is 0.81, the mechanical efficiency is 0.8. The mechanical efficiency of working fluid pump is 0.75. The condensing temperature of two organic Rankine cycle system is 298K. Thinking that when the exhaust temperature is lower than the acid dew point, it will corrode the pipe. Therefore, the exhaust temperature of the evaporator is set to 418K\(^[6]\). According to the established thermodynamic model, the influence of the evaporation temperature and expansion ratio of the refrigerant on the performance of the system can be analyzed. The physical parameters of organic matter at each state point are retrieved by REFPROP9.0.

<table>
<thead>
<tr>
<th>Rotation rate</th>
<th>Torque</th>
<th>Power</th>
<th>Specific heat capacity at constant pressure</th>
<th>Turbine temperature</th>
<th>Mass flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>r/min</td>
<td>N·m</td>
<td>kW</td>
<td>kJ/(kg·K)</td>
<td>K</td>
<td>kg/s</td>
</tr>
<tr>
<td>1600</td>
<td>2000</td>
<td>335.6</td>
<td>1.145</td>
<td>702</td>
<td>0.4306</td>
</tr>
</tbody>
</table>
Figure 5. The variation of net output power with evaporation temperature in two systems.

Calculation Result and Analysis

The figures 5 (a) and 5(b) are shown the expansion ratio in the range of 3~7. The net power output of the ordinary Rankine cycle and two organic Rankine cycle 1 system changes with refrigerant evaporation temperature.

As can be seen in Figure 5(a), when the evaporating temperature is constant, the net output power of the system increases with the expansion ratio. When the expansion ratio is constant, the net output power of the system decreases slowly with the increase of temperature. When the expansion ratio is 7 and the working temperature is 430 K, the net output power of the system reaches the maximum value 11.4 kW.

As can be seen in Figure 5(b), when the evaporation temperature of the working medium is constant, the net output power of the system decreases with the increase of expansion ratio. When the expansion ratio is constant, with the increase of evaporation temperature of the working medium, the net output power of the system increases first and then decreases. When the system stage expansion ratio is 3, the refrigerant evaporation temperature is 460 K, the net power output of the system reaches the maximum value of 14.13 kW.

The figure 6(a), 6(b) represents the thermal efficiency of the ordinary Rankine cycle system and two level of organic Rankine cycle system in different expansion ratio with the change of evaporation temperature. The evaporating temperature of the working medium is set in the range of 390-470 K. When the system has a definite heat transfer rate, the system thermal efficiency is only related to the net output power. The figure 6(a) shows that, when the expansion ratio is 7 and the evaporation temperature is 431 K, the efficiency of the basic organic Rankine cycle system reaches the maximum value of 10.1%. When the system is shown in Figure 6(b), the first level expansion ratio is 3, the refrigerant evaporation temperature is 460 K, the thermal efficiency of two organic Rankine cycle system reaches the maximum value of 12.67%. The comparison shows that the thermal efficiency of two organic
Rankine cycle system thermal efficiency is higher than the ordinary organic Rankine cycle system.

![Graph showing the change of thermal efficiency with evaporating temperature](image)

Figure 6. The change of thermal efficiency of two systems with evaporating temperature.

**CONCLUSIONS**

1. Compared to the two level of organic Rankine cycle system and common organic Rankine cycle system, the former has a net output power, high heat utilization rate. The net output power of the system is up to 14.13kW, the maximum utilization rate of heat is 12.67%, and the recovery of waste heat is better;

2. Evaporation temperature and expansion ratio have significant influence on system thermodynamics. In practical application, proper evaporation temperature and expansion ratio should be selected so as to improve the efficiency of the system.

**REFERENCES**