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Energy Performance Comparison of Heat Pump and Power Cycles in Waste Heat Recovery

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A chemical process usually needs to combust fossil fuels to provide the energy required for production, then a large number of low temperature waste heat is discharged to the environment. Recovery of such waste heat plays an important role in saving primary energy and protecting the environment. There are many waste heat recovery technologies, among which heat pump and power cycles are widely used. In order to make a proper choice of the utilization mode for the low temperature waste heat, the simulation models of mechanical heat pump, steam turbine and Organic Rankine Cycle are established in this paper. Calculations are made under different waste steam temperatures (100 °C to 150 °C) and different heat pump temperature lifts (10 °C, 15 °C, 30 °C). Exergy efficiency is used as the index to compare the energy performance of the three waste heat recovery cycles. The results show that the exergy efficiency of the mechanical heat pump is always higher than 0.9, while that of the Organic Rankine Cycle and steam turbine is between 0.3 and 0.5. The exergy efficiency of the mechanical heat pump is always highest under any working conditions. Based on energy performance, the mechanical heat pump is always a better choice than a power cycle in low-temperature waste heat recovery. Besides, the energy performance of the Organic Rankine Cycle is better than that of the steam turbine. This article compares these two waste heat recovery technologies with completely different working principles, and can provide a reference for factories to choose a suitable waste heat recovery technology.

1. Introduction

There is a huge number of waste heat in industrial processes, accounting for 72 % of the consumed primary energy, in which 60 % is low-temperature waste heat below 230 °C (Forman et al., 2016). Although the amount of waste heat is large, the grade of such heat is low. It is normally difficult to recover them directly. The low-temperature waste heat can be converted into higher-grade heat, cold capacity or work. Heat pump cycles are used to upgrade the quality of waste heat, refrigeration cycles convert heat into cold capacity, and heat engine cycles convert heat into work. These technologies are widely used in industrial waste heat recovery. Comparing different waste heat recovery technologies can provide factories with selection references.

There are many studies on the comparison of the same type of waste heat recovery technologies. At present, the most widely used heat pumps in the industry are mechanical heat pumps (MHPs, also called compression heat pumps in some literatures) and absorption heat pumps (AHPs). Sun et al. (2014) compared the AHP with the MHP based on the coefficient of performance and primary energy utilization. The results show that the coefficient of performance of the MHP is much greater than that of the absorption heat pump. The research results of Wang et al. (2020) are consistent with those of Sun et al (2014), showing that under the same working conditions, the coefficient of performance of the MHP is always higher than that of the AHP and absorption heat transformer. Farshi et al. (2018) conducted thermodynamic analysis and comparison of the cascaded compression-absorption, compression, absorption, and hybrid compression-absorption heat pumps. The results show that the cascaded compression-absorption heat pump has the advantages of small compression ratio, maximum compression pressure and low outlet temperature, and the exergy efficiency and primary energy utilization of the compression heat pump are always higher than that of the AHP. Razmi et al. (2018) analysed the coefficient of performance, exergy destruction and irreversibility of the absorption/recompression, compression, and absorption heat pumps at different generator and evaporator temperatures. The results show

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that the compression heat pump has the highest coefficient of performance, while the AHP has the lowest within the range of studied working conditions. From the perspective of exergy efficiency, when the generator temperature is lower than 60 °C and the evaporator temperature is low, the exergy efficiency of the absorption/recompression heat pump may be higher than that of the compression heat pump. In most other working conditions, the compression heat pump has the highest exergy efficiency, and the index of the compression heat pump is always higher than that of the AHP. Based on the comparison in literatures, it can be seen that the MHP has better energy performance than the AHP. This article takes the vapour mechanical heat pump as a representative of heat pump cycles.

Heat engines include Karina Cycles (KCs), Organic Rankine Cycles (ORCs), Steam Rankine Cycles (SRCs) and so on. Zhang et al. (2016) established mathematical models of the SRC, ORC and Steam-Organic Rankine Cycle (S-ORC), and compared them based on thermal efficiency, exergy efficiency, operation pressure and generation capacity. The results show that the ORC has the highest thermal efficiency, exergy efficiency and power generation when the waste heat temperatures are 150-210 °C; while at 210-350 °C, the performance of the S-ORC has manifest advantage. Noroozian et al. (2019) compared and optimized the transcritical CO_2, ORC and trilateral Rankine cycles. The results show that the ORC with R123 as the working fluid had the highest thermal efficiency, the transcritical CO_2 cycle had the highest exergy efficiency, and the ORC with R245fa has the lowest product cost ratio. Milewski and Krasucki (2017) studied the performance of KCs and ORCs with different working fluids in the waste heat recovery of the steel industry. The ORC cycle with butylbenzene as the working fluid has the highest system efficiency below 200 °C, and when the temperature is higher than 200 °C, the KC becomes competitive. It can be seen that the advantages and disadvantages of the ORC and KC are not absolute, but a large number of studies have shown that the KC has more advantages when the heat source temperature is high, while the ORC is suitable for low-temperature heat sources (Walraven et al., 2013）.

The working principles of heat pumps and heat engines are quite different, but usually heat pumps utilize the waste heat under 80-150 °C, while heat engines under 100~300 °C (Gangar et al., 2020). The two cycles have a cross-over waste heat utilization range. If a certain waste heat is available under such cross-over temperature range, it is indispensable for the factory to choose a proper waste heat recovery technology so that more energy can be saved.

This study compares the energy performance of heat pumps and heat engines in low-temperature waste heat recovery for the first time. The mechanical heat pump is selected as the representative of heat pumps because of its excellent energy performance. For heat engines, since the temperature of the waste heat used by the heat pump is relatively low, and the Organic Rankine Cycle shows stronger competitiveness under low-temperature, this article takes the Organic Rankine Cycle as a representative of heat engine. In addition, as this article considers waste heat steam as the waste heat source, a steam turbine which can directly utilize steam and has simple structures is also included in the comparison. Based on the simulation results of these three cycles, the energy performance of the three systems under different working conditions is compared by using exergy efficiency as the performance index. The work in this paper can provide a reference for industrial waste heat recovery.

2. Simulation models

For the purpose of making a comparison between the three systems under different working conditions, the temperatures of the waste heat and the temperature lifts of the heat pump are considered as independent variables in this paper. The two parameters are changed in the range of 100~150 °C and 10~30 °C, and the flow rate of the waste heat source is taken as 1.1 kg/s. The flow rate of the working fluid depends on the waste heat and output power. When the waste heat and minimum temperature difference are given, the working fluid flow rate should be the one which makes the output power of the turbine reach the maximum. All three systems are simulated in Aspen Plus V10 (AspenTech, 2017).

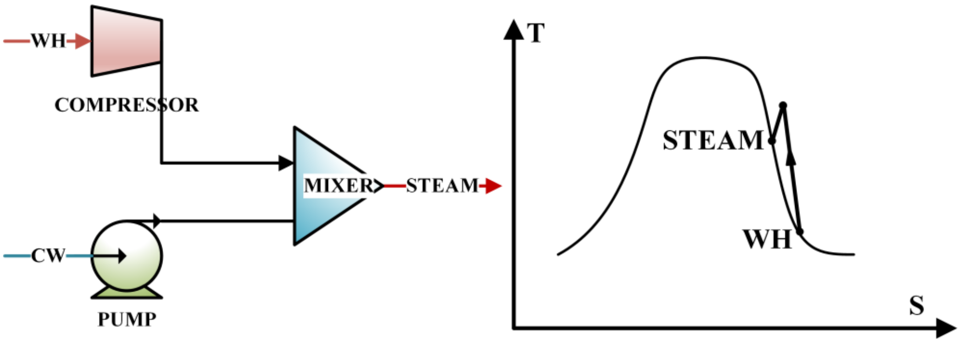
2.1 Mechanical heat pump (MHP)

An open cycle mechanical heat pump is considered in this article, which consists of a compressor, pump and mixer. The schematic and temperature-entropy diagrams of the MHP are shown in Figure 1.

The low-temperature waste heat steam is compressed into superheated steam by the compressor, mixed with the water pressurized by the pump to become saturated steam, and finally output to the user side. Water is used as the working fluid, so steamNBS is chosen as the physical property method (Haar et al, 1984). The power of the pump is much smaller than that of the compressor and can be ignored in the calculation. Its efficiency can be taken as 1. According to literature data, the isentropic efficiency of the compressor is taken as 0.7 (Bor and Ferreira, 2013). In addition, it is assumed that there is no pressure drop in the mixer.

2.2 Organic Rankine Cycle (ORC)

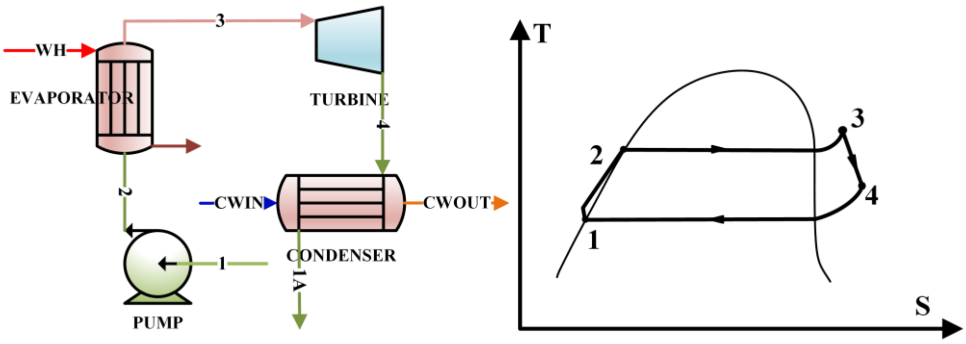
The schematic and temperature-entropy diagrams of the Organic Rankine Cycle are shown in Figure 2. The cycle consists of a pump, evaporator, turbine and condenser. The working fluid enters the pump and is pressurized, and then enters the evaporator to absorb the heat from the waste heat source and becomes saturated vapor or superheated vapor. The working vapor then enters the turbine to generate work. After the thermal energy is converted into mechanical work, the working fluid enters the condenser and becomes saturated liquid. The condensed liquid enters the pump again, completing a cycle. R123 is used as the working fluid, and the REFPROP method is selected as the physical property method (Galashov et al., 2016).



(a) *(b)*

Figure 1: (a) Schematic diagram of open cycle MHP; (b) Temperature-entropy diagram

According to the research of Bao and Zhao (2013), the isentropic efficiency of the turbine can reach 0.85 in the power range of 15~200 kW. The power of the ORC studied in this paper is about 200 kW, and the isentropic efficiency of the turbine is taken as 0.75. The efficiency of the pump is taken as 0.8 (Kazemi and Samadi, 2016). In addition, it is assumed that there is no pressure drop in the evaporator and condenser. The outlet working vapor of the evaporator (point 3 in Figure 2) is assumed to be saturated vapor, and the outlet stream of the condenser (point 1A in Figure 2) is assumed to be saturated liquid. The temperature difference of the evaporator remains unchanged under different working conditions.

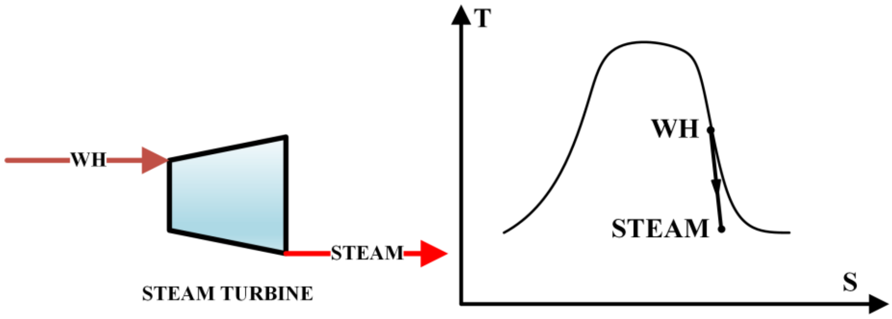


(a) *(b)*

Figure 2: (a) Schematic diagram of ORC; (b) Temperature-entropy diagram

2.3 Steam turbine (ST)

Figure 3 shows the schematic and temperature-entropy diagrams of a steam turbine. A steam turbine can also convert thermal energy into mechanical work. The waste heat steam enters the ST and converts the heat of the steam into mechanical work. Only water is involved in this process, so steamNBS is chosen as the physical property method (Haar et al, 1984). According to the research of Andreasen et al. (2017), the efficiency of a single-stage steam turbine with a power of 1,356 kW can reach 0.65. In this paper, the efficiency of the steam turbine is lower than 300 kW, so the efficiency is taken as 0.6.



(a) *(b)*

Figure 3: (a) Schematic diagram of ST; (b) Temperature-entropy diagram

3. Evaluation index

For different cycles consume and produce different types of energy, the concept of exergy is introduced to characterize the quality or grade of energy, and exergy efficiency is used as the evaluation index, which is represented by the symbol $\boldsymbol{\eta}$. The calculation of physical exergy is shown in Eq(1).

$$E = m \cdot [h - h_0 - T_0(s - s_0)] \quad (1)$$

where m refers to the mass flow rate of streams. h and h_0 refer to the specific enthalpy of a stream in the current and reference states. T_0 represents reference temperature, taken as 298.15 K. s and s_0 mean specific entropy of a stream in current and reference conditions.
In this paper, the exergy values of streams are obtained by Aspen Plus V10 simulation.
The general formula for calculating the exergy efficiency of the three cycles is shown in Eq(2).

$$\eta = \frac{E_{PRODUCT}}{E_{LSIN} + E_{CWIN} + E_x} \quad (2)$$

where E refers to the exergy of streams. The subscripts PRODUCT, LSIN, and CWIN represent the output (heat flow or mechanical work), the input waste heat source and the cold water. Ex refers to the mechanical exergy input, including the mechanical work of the compressor and the pump.
The relative magnitude of exergy efficiency reflects the energy performance of different cycles.

4. Results and discussion

According to the simulation results, the exergy efficiencies of the MHP, ORC and ST under different waste heat temperatures and heat pump temperature lifts are calculated, and the results are shown in Figure 4. The input work of the MHP and the output work of the ORC and ST are shown in Table 1.
The heat pump temperature lift has no effect on the energy performance of the two heat engine cycles, but only affects the exergy efficiency of the MHP. At the same waste heat temperature, the exergy efficiency of the MHP decreases with the increase of the heat pump temperature lift. For the waste heat sources with the same quantity heat and temperature, a higher temperature lift relies on a larger mechanical energy input by the compressor, so the input work will increase. The mechanical work input by the compressor is energy with better quality than thermal energy. The more input is, the greater the exergy loss and the lower the exergy efficiency will be. A higher temperature lift will lead to lower exergy efficiency of the heat hump.
The waste heat temperature has an impact on the energy performance of all the three cycles. When the waste heat temperature increases, all the exergy efficiencies of the MHP, ORC and ST improve. For the MHP, if the temperature of the waste heat grows up, the enthalpy difference between the product and the waste heat will decrease under the same temperature lift. This is determined by the physical properties of water. The input work of the compressor goes down with the increase of the waste heat temperature, and the exergy loss from mechanical energy to heat also decreases, so the exergy efficiency increases. For the ORC and ST, as the temperature of the waste heat increases, the heat which can be used increases, so the turbine can generate more work. As a consequence, the exergy efficiency increases.
It can be seen from Figure 4 that no matter how the waste heat temperature and the temperature lift of the heat pump change, the exergy efficiency of the MHP is always the highest, and the exergy efficiency of the ST is always the lowest. This is because the MHP converts all the waste heat and the work of the compressor into

the thermal energy of the output steam in the process, while the streams at the outlet of the turbine for the ORC and ST have a part of the energy which cannot do work, which is finally absorbed by the cooling water, caused a greater exergy loss. The exergy efficiency of these two systems is much lower than that of the MHP.
The ORC and ST use R123 and waste heat steam as working fluids. The evaporation pressure of R123 at low temperature is much higher than the saturation pressure of the waste heat steam, so it has stronger capability to do work in the turbine. The ORC does more work under the same waste heat conditions, and the exergy efficiency is higher.

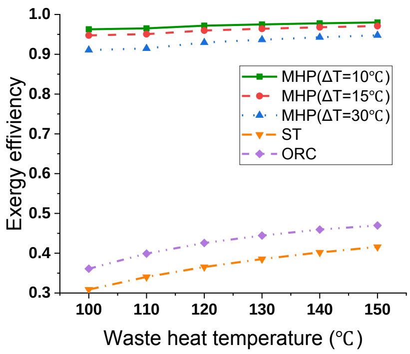


Figure 4: The exergy efficiency of the three cycles varies with the temperature of the waste heat at different heat pump temperature lifts

Table 1: Input work of the MHP and output work of the ORC and ST under different working conditions

	Work input / kW			Work output / kW	
Waste heat temperature / °C	MHP (ΔT=10 °C)	MHP (ΔT=15 °C)	MHP (ΔT=30 °C)	ST	ORC
100	96	145	295	166	192
110	92	139	282	201	233
120	89	134	271	235	271
130	86	129	260	267	304
140	82	124	249	297	334
150	79	119	239	326	362

5. Conclusion

In this paper, energy performance of two waste heat recovery technologies with completely different working principles, heat pumps and heat engines, are compared to provide a reference for factories to recover low-temperature waste heat. The conclusions are as follows.
1. As the temperature lift increases, the exergy efficiency of the mechanical heat pump decreases. The exergy efficiency of MHP reaches the highest at a temperature lift of 10 °C when the waste heat is 150 °C, which is 0.98.
2. As the waste heat temperature increases, the exergy efficiency of the mechanical heat pump, Organic Rankine Cycle and steam turbine increases. The highest exergy efficiency of Organic Rankine Cycle and steam turbine reaches the highest at 150 °C, which are 0.47 and 0.42.
3. From the perspective of exergy efficiency, the mechanical heat pump is always better than heat engines, and the Organic Rankine Cycle is better than the steam turbine.
Future work should focus on economic comparison, including investment costs and operating costs. The total cost under different ratio of heat and electricity prices will be investigated.

Nomenclature

Acronyms
AHP – absorption heat pump
KC – Karina Cycle
MHP – mechanical heat pump
SRC – Steam Rankine Cycle
ST – steam turbine
ORC – Organic Rankine Cycle

Greek letters

ΔT– temperature lift, °C

η – exergy efficiency, -

Parameters
E – physical exergy, kW
E_{CWIN} – physical exergy of cold water, kW
E_{LSIN} – physical exergy of waste heat, kW
$E_{PRODUCT}$ – exergy of output steam or mechanical work, kW
E_x – input exergy of compressor and pump, kW T_0 – reference temperature, K
h – specific enthalpy of a stream under the current state, kJ/kg
h_0 – specific enthalpy of a stream under reference state, kJ/kg
m – mass flow rate, kg/s
s – specific entropy of a stream under current state, kJ/(kg·K)
s_0 – specific entropy of a stream under reference state, kJ/(kg·K)

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