PERFORMANCE ANALYSIS OF LOW-TEMPERATURE ORGANIC RANKINE CYCLE USING HFO WORKING FLUIDS AND SINGLE SCREW EXPANDER

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ABSTRACT

The organic Rankine cycle (ORC) is a popular technology used in waste heat recovery and medium-low-temperature heat utilization. In the field of low-temperature heat utilization, the net work output and thermal efficiency are two critical evaluation indicators of ORC system due to the low grade of heat source. Nowadays, as environmentally friendly working fluids, hydrofluoroolefins (HFOs) have attracted more and more attention. Moreover, as a novel expander, single-screw expander also becomes research focus. Compared with other type expander, one of the advantages of single-screw configuration is that it can conduct a vapor-liquid wet expansion. In order to use this advantage, an ORC using single-screw expander and R1234yf and R1234ze, two popular HFO working fluids, was established. Net work output is the critical evaluation indicator for open type heat source. While thermal efficiency is the one for closed type heat source. Heat exchange load of condenser is the critical indicator for calculating the cost of condenser that greatly influences the cost and economic performance of entire ORC system. Therefore, three indicators, namely net work output, thermal efficiency, and heat exchange load of expander, were used to analyze the performance of an ORC system using HFO working fluid and single-screw expander. Through calculation and analysis, it can be seen that compared with the traditional cycle process, the ORC system which uses single-screw expander and undergoes a vapor-liquid wet expansion can obtain a higher thermal efficiency, more net work output, and smaller heat exchange load of condenser.

1. INTRODUCTION

In order to alleviate the energy crisis around the world and to solve the environmental problems caused by the consumption of traditional energy sources, two important measures have to be adopted. One is renewable and sustainable energy utilization, and other is low-grade waste heat recovery. The organic Rankine cycle (ORC) is a promising and popular technology used in above two measures.

In ORC, organic working fluid plays a decisive role. The working fluid selection can greatly affect economic feasibility of an ORC while the economic performance of ORC system is an important factor affecting its application and development. Moreover, the impact on the environment is also greatly affected by working fluid selection. From a historical perspective, CFCs and HCFCs dominated organic working fluids from 1931 to early 1990s. Since the ratification of the Montreal Protocol in 1987 and the Kyoto Protocol in 1997, more and more attention has been paid to the development of environmentally friendly organic working fluids. Therefore, based on environmental concerns, CFC working fluids have been phased out and HCFC working fluids will be phased out by

2040 for developing countries. Nowadays, One trend in developing new organic working fluids is organic synthesis of new working fluid with a zero Ozone depletion Potential (ODP) and a low Global Warming Potential (GWP) (Duvedi and Achenie, 1996, 1997). Therefore, HFO working fluids are drawing more and more attention. R1234yf and R1234ze are two typical HFO working fluids that have recently been studied and used frequently.

Among the four devices making up an ORC, the expander is the critical component because it determines the efficiency and cost of an ORC. Expanders, in general, can be categorized into two types: the turbo type and the positive-displacement type. Large scale ORC systems normally adopt turbo expanders (Bao and Zhao, 2013; Quijano *et al.*, 2012). However, for small scale ORC unit, turbo expander might not be favorable (Wang *et al.*, 2016). Positive-displacement expanders, such as rolling piston expander, scroll expander, and single screw expander, are good substitutes for turbo machines due to their relatively high efficiency, high pressure ratio, low rotational speed, and tolerance of two-phase fluids (Bao and Zhao, 2013). When the output power is larger than 3.5 kW, single screw expander seems more promising. Compared to scroll expander and rolling piston expander, it has many advantages, such as balanced load of the screw, long service life, high volume efficiency, good performances in partial load, low leakage, low noise, low vibration and simple configuration (Wang *et al.*,2011, 2013; Wu *et al.* 2013). The isentropic efficiencies of four single screw expanders developed by our research team are depicted by Figure 1-4. As mentioned above, single screw expander can tolerate two-phase expansion. Therefore, in this paper, an ORC using single-screw expander and R1234yf and R1234ze, two popular HFO working fluids, is established. Three indicators, namely net work output, thermal efficiency, and heat exchange load of expander, are used to analyze the performance of an ORC system using HFO working fluid and single-screw expander.

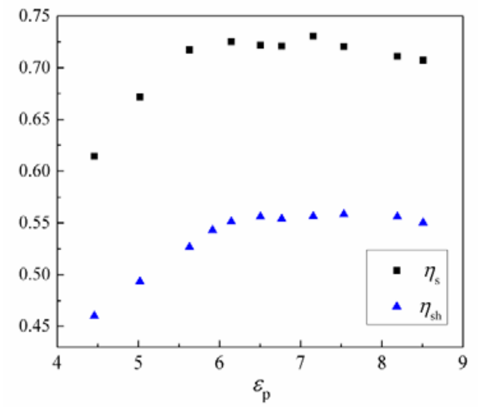

Figure 1: Variation of shaft efficiency and isentropic efficiency with expansion ratio for a single screw expander (external diameter Ø117) with a large expansion ratio

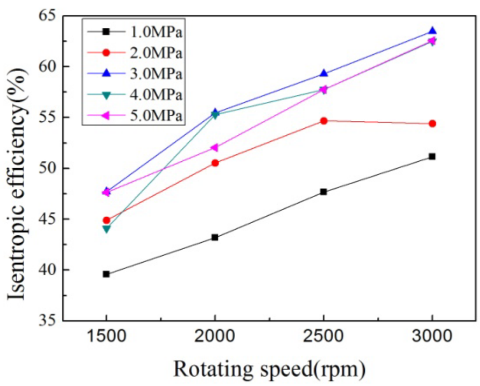

Figure 2: Variation of isentropic efficiency with rotating speed for a single screw expander (external diameter Ø117) used in high pressure condition

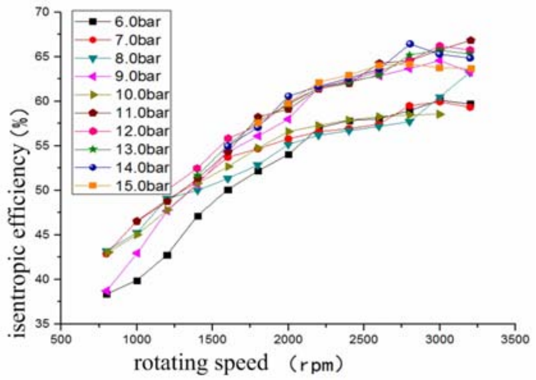

Figure 3: Variation of isentropic efficiency with rotating speed for a single screw expander (external diameter Ø200)

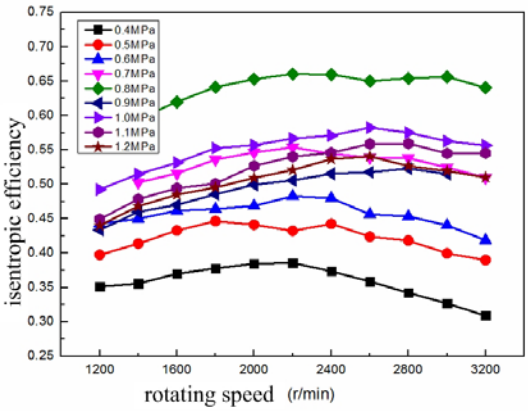

Figure 4: Variation of isentropic efficiency with rotating speed for a single screw expander (external diameter Ø350)

2. METHODOLOGY

As mentioned in the last section, single-screw expander can conduct a vapor-liquid wet expansion. Therefore, a new working process of ORC using HFO working fluids and single screw expander was designed and Figure 5 depicts this process. From Figure 5, it can be seen that the process 4-5 is a two-phase isentropic expansion. Both state point 4 and 5 are at the saturated vapor curve. On the contrary, the traditional working process of ORC with isentropic working fluid is depicted in Figure 6. In Figure 6, the state point 5, the end of isentropic expansion, is at superheated state. The state point 4 is still at the saturated vapor curve. Here it should be noted that due to the material limitation of star wheel, the maximum working temperature of single screw expander cannot exceed 130℃. Therefore, the temperature of state point 4 cannot exceed 130℃ in both the two-phase expansion process and the traditional working process.

In order to compare the performance of these two working modes, the same condensation temperature in both working mode is set. As for the two-phase expansion working mode, the entropy of state point 5 can be determined according to the condensation temperature. Then the temperature of state point 4 can be determined according to its entropy value that is the same as that of state point 5. As for the traditional working mode, the temperature of state point 4 is set to be the temperature of the turning point on saturated vapor curve of isentropic fluid whose entropy value reaches the maximum ranging from normal boiling point to critical point (Zhang *et al.*, 2019a). The temperature of state point 6 is determined according to the condensation temperature.

There are two types of waste heat (Yan, 1982; Liu *et al.*, 2014), open type and closed type. For the open type, the inlet temperature and the mass flow rate are known, and the working mass of the heat source is directly discharged after being used. For the closed type, the heat release is specific and the working mass of the heat source is usually recycled after releasing heat. Therefore, the standards used to measure the waste heat recovery of these two types of heat source are different (Yan, 1982). The maximum net power output is used as the criterion for the open type while the maximum thermal efficiency is for the closed type. Therefore, net power output and thermal efficiency are adopted as the first two indicators for evaluating the performance of two-phase expansion working mode and traditional working mode of ORC. The third evaluation indicator is heat exchange load of condenser because it is the critical for calculating the cost of condenser that greatly influences the cost and economic performance of entire ORC system (Zhang *et al.*, 2019b).

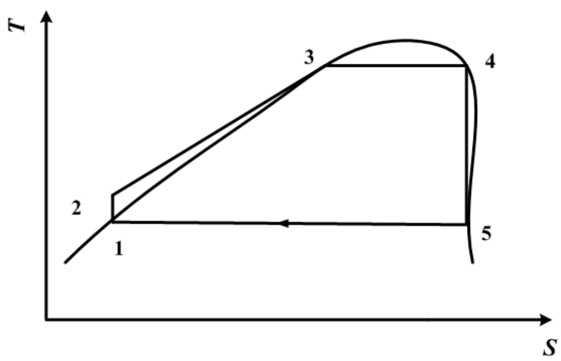

Figure 5: Two-phase expansion working mode of ORC using HFO working fluids and single screw expander

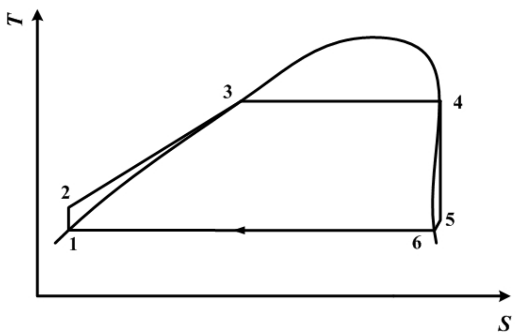

Figure 6: Traditional working mode of ORC with isentropic working fluid

Based on the above consideration and the working process depicted in Figure 5 and Figure 6, net power output can be calculated from the following equation.

$$W_{\mathrm{net}} = (h_4 - h_5) - (h_2 - h_1) \tag{1}$$

The thermal efficiency can be calculated by

$$\eta = \frac{W_{\mathrm{net}}}{Q_{\mathrm{e}}} = \frac{(h_4 - h_5) - (h_2 - h_1)}{h_4 - h_2} \tag{2}$$

The heat exchange load of condenser can be calculated by

$$Q_{\mathrm{c}} = h_5 - h_1 \tag{3}$$

In the above equations, *h* denotes enthalpy value in the unit of kJ·kg^{-1}, *w* denotes work in the unit of kJ·kg^{-1}, and *q* denotes heat in the unit of kJ·kg^{-1}. The number on subscript stands for the state point of the ORC. The letter e on subscript stands for evaporator and c for condenser. All the thermophysical values come from NIST REFPROP 9.1.

3. RESULTS AND DISCUSSION

When R1234yf and R1234ze are used as the working fluids of ORC, the condensation temperature, the evaporation temperatures, and the net power output of above two working modes are listed in Table 1. Table 2 lists the comparison of thermal efficiency of above two working modes. Table 3 lists the comparison of heat exchange load of condenser.

Table 1: Condensation temperature, evaporation temperatures, and net power output of two-phase expansion working mode and traditional working mode of ORC

Working Fluid	Condensation Temperature / K	Evaporation Temperature of two-phase expansion working mode / K	Evaporation Temperature of Traditional Working Mode / K	Net power output of two-phase expansion working mode / kJ·kg^{-1}	Net power output of Traditional Working Mode/ kJ·kg^{-1}
R1234yf	300	347.6	329	17.74	12.17
	305	345.4	329	14.87	9.8
	310	343.2	329	11.99	7.53
	315	340.4	329	9.05	5.38
	320	337	329	6.01	3.36
R1234ze	300	359.5	340	24.97	18.71
	305	358	340	21.848	15.981
	310	356	340	18.706	13.351
	315	354	340	15.596	10.858
	320	351	340	12.308	8.451

Table 2: Condensation temperature, evaporation temperatures, and thermal efficiency of two-phase expansion working mode and traditional working mode of ORC

Working Fluid	Condensation Temperature / K	Evaporation Temperature of two-phase expansion working mode / K	Evaporation Temperature of Traditional Working Mode / K	Thermal efficiency of two-phase expansion working mode / %	Thermal efficiency of Traditional Working Mode / %
R1234yf	300	347.6	329	10.98	7.72
	305	345.4	329	9.62	6.51
	310	343.2	329	8.15	5.24
	315	340.4	329	6.49	3.95
	320	337	329	4.57	2.60
R1234ze	300	359.5	340	13.11	10.06
	305	358	340	11.91	8.93
	310	356	340	10.62	7.76
	315	354	340	9.24	6.58
	320	351	340	7.65	5.36

Table 3: Condensation temperature, the evaporation temperatures, and heat exchange load of condenser of two-phase expansion working mode and traditional working mode of ORC

Working Fluid	Condensation Temperature / K	Evaporation Temperature of two-phase expansion working mode / K	Evaporation Temperature of Traditional Working Mode / K	Heat exchange load of two-phase expansion working mode / kJ·kg^{-1}	Heat exchange load of Traditional Working Mode/ kJ·kg^{-1}
R1234yf	300	347.6	329	143.87	145.45
	305	345.4	329	139.65	140.85
	310	343.2	329	135.21	136.04
	315	340.4	329	130.49	130.99
	320	337	329	125.47	125.7
R1234ze	300	359.5	340	165.51	167.27
	305	358	340	161.586	163.059
	310	356	340	157.484	158.659
	315	354	340	153.184	154.052
	320	351	340	148.662	149.239

From the above three tables, it can be seen that at the same condensation temperature, the ORC system which uses single-screw expander and undergoes a vapor-liquid wet expansion can obtain a higher thermal efficiency, more net work output, and smaller heat exchange load of condenser. The thermodynamic performance of two-phase expansion working mode is better than that of traditional working mode.

4. CONCLUSIONS

In order to take advantage of two-phase expansion of single screw expander, an ORC using R1234yf and R1234ze, two popular HFO working fluids, was established. Three indicators, namely net work output that is used for evaluating open type heat source, thermal efficiency that is used for evaluating closed type heat source, and heat exchange load of condenser that greatly influences the cost and economic performance of entire ORC system, were used to analyze the performance of an ORC of two-phase expansion working mode and traditional working mode. Through calculation and analysis, it can be seen that compared with the traditional cycle process, the ORC system which uses single-screw expander and undergoes a vapor-liquid wet expansion can obtain a higher thermal efficiency, more net work output, and smaller heat exchange load of condenser.

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