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Performance analysis of a novel organic Rankine cycle with a vapor-liquid ejector

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ABSTRACT

Organic Rankine cycle (ORC) is a promising technology of converting the low-grade thermal energy to electricity. But the pump work accounts for a large percentage of the expander output power in the small-scale system, which greatly worsens the system efficiency. In this paper, a novel organic Rankine cycle with a vapor-liquid ejector (EORC) is proposed to enhance the system performance. It is compared to the conventional ORC and a regenerative organic Rankine cycle (RORC), and the results show that it has higher system efficiency when the pump has a low efficiency and the evaporating temperature is high. A parametrical study on this novel system is further carried out with three working fluids, namely, R123, R1233zd(E) and R1336mzz(Z). The ejector behavior and system performance are strongly interacted, which are elaborated and discussed. There exists an optimal ejector entrainment ratio that minimizes the pump work and maximizes the system efficiency. The ejector area ratio and the subcooling at the condenser outlet have great influence on the ejector pressure lift, leading to the significant variations of temperature in the evaporator I, however, their influence on the expander output power is moderate. As for the condensing temperature, it has remarkable effect on system performance except the ejector pressure lift. The three candidates have similar features of variations for the considered variables. R1233zd(E) is recommended as the good working fluid since it has higher system efficiency than R1336mzz(Z) and is more favored by the environment than R123.

1. Introduction

Converting low-grade thermal energy to electricity is a viable approach to reduce the fossil fuel consumption with the benefit of providing a sustainable environment, and thus has drawn unprecedented attentions in recent years [1]. In particular, the low-grade thermal energy is abundant with a feature of low temperature. For instances, solar heat with a temperature lower than 200 °C can be easily and cheaply obtained by the non-focusing collectors [2], the geothermal temperature is generally lower than 240 °C [3], and approximately 60% of industrial waste heat is lower than 230 °C [4]. Another characteristic of the low-grade thermal energy is the low energy density and strong dispersion. Solar radiation is generally less than 1000 W/m^2, making a large collector area for the desirable amount of energy not easily accessed, and more than 90% of available waste heat worldwide is applicable to 10–250 kW system size [5].

Among the low-grade thermal-electricity technologies, organic Rankine cycle (ORC) is considered to be very promising because, on one hand, it is able to effectively utilize the low temperature thermal energy with simple mechanism and better economy; on the other hand, it is flexible for different system sizes [6], which are very suitable for the low-grade thermal energy recovery. Moreover, it is simple and has four main components: the evaporator, the expander, the condenser and the pump, as shown in Fig. 1.

The pump pressurizes the working fluid from condensing pressure to evaporating pressure. In small-scale ORC, the pump is characterized by low flow rate and high pressure rise. More importantly, it has some issues to be addressed as: (1) the pumping technology in small scale applications cannot benefit of the efficiency figures that are available for large scale systems, and a small pump normally trend to have low efficiency [7,8]; (2) the temperature level and heat quantity of heat source/sink are usually subjected to vary during operation. Hence the pump sometimes operates at off-design conditions [9]; (3) the internal leakage is aggravated by the working fluid with large pressure difference and low viscosity, which has large influence on the mechanical losses [9,10]; (4) cavitation is more serious for the organic fluids that usually have lower evaporation temperature and latent heat than water, and it weakens the pump performance [11]. Therefore, ORC pump should always operate

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Nomenclature

Symbols

A	area (m^2)
Ar	ejector area ratio
F	wall resistance (N)
h	enthalpy (kJ/kg)
ṁ	mass flow rate (kg/s)
P	pressure (MPa)
PL	Pressure lift
Q	heat load (kW)
s	entropy (kJ/kg·K)
T	temperature (°C)
Δ*T*	temperature difference (°C)
U	entrainment ratio
u	velocity (m/s)
W	power (kW)

Greeks

η	efficiency
ρ	mass density (kg/m^3)
ψ	ejector coefficient

Subscripts

a–f	positions of ejector in Fig. 4
CO	condenser
DI	ejector diffuser
EV	evaporator
EV1	evaporator I in EORC
EV2	evaporator II in EORC
EX	expander
l	liquid
NO	ejector vapor nozzle
PU	pump
Sink	heat sink
Source	heat source
SYS	system
t	vapor nozzle throat
v	vapor
1–11	states of systems in Figs. 1–4

above the cavitation limit. However, increasing cavitation margin reduces system thermal efficiency [12]. Therefore, the pump in small-scale ORC has rather low efficiency. In practical, the measured values of 16.2% [8], 11–23% [13], 7–25% [14] and 15–65.7% [9] are reported. In other words, a large amount of electricity is consumed by the pump. For the small-scale ORC with low temperature heat source, this cannot be neglected and thus could be a vital factor to the reduction of the system efficiency [15,16]. Therefore, the back work ratio (BWR), defined as the ratio between the pump work and the expander output power [14], can be substantially high. Miao et al. [17] and Feng et al. [18] claimed that BWR was 22.9% and 32%, respectively. It was also reported that BWR could be 42% [19], 45% [9] and as high as 77.5% [20]. The system net output power could be negative at some worst scenarios [8]. Table 1 gives a simple overview of the typical results in this regard. As a result, the pump work in the small-scale ORC needs to be paid much attention on.

To improve the ORC system efficiency, researchers have devoted their efforts to eliminate the pump. Li et al. [21] utilized gravity of the working fluid to drive ORC, and the performance was 0.9% higher, however, with a requirement of 20.9 m of height. Yamada et al. [22] proposed a pumpless ORC by switching the heat source and heat sink between the evaporator and condenser. Gao et al. [23] and Jiang et al. [24] carried out further investigations on this pumpless ORC under different operating conditions and higher output power, the obtained maximum system efficiency was 2.4%. Richardson [25] introduced a bypass of high pressure vapor in the evaporator to pressurize the liquid in the condenser to replace the pump; however, it leads to the decreasing of expender output power due to reduced mass flow rate. It seems that the system improvement by eliminating the pump is limited.

Researchers have also tried to reduce the pump work instead of completely replacing the pump. The ejector is a flow device that allows a high pressure fluid, termed the primary fluid, to entrain a low pressure fluid (the secondary fluid) into the flow path, and discharges the mixed flow at a higher pressure, acting like a compressor or a pump without any external energy input. The vapor-liquid ejector has the ability to elevate pressure of the mixed flow to the level that is even higher than the primary fluid [26]. In principle, it uses latent heat of the primary vapor to pressurize and heat the liquid [27], and is also call as condensing ejector. Xu et al. [28] introduced a regenerative ORC (RORC) by adopting the vapor-liquid ejector in a way of extracting vapor with intermediate pressure from the expender to induce the liquid from the condenser, and discharging to the pump, as illustrated in Fig. 2. The vapor-liquid ejector plays the role of a regenerator, and reduces the pump work as the pump inlet pressure is increased. In this RORC, the expander output power is subjected to reduce since a part of vapor with intermediate pressure is used in the ejector without producing power. Its system efficiency could reach 18.03%, which was

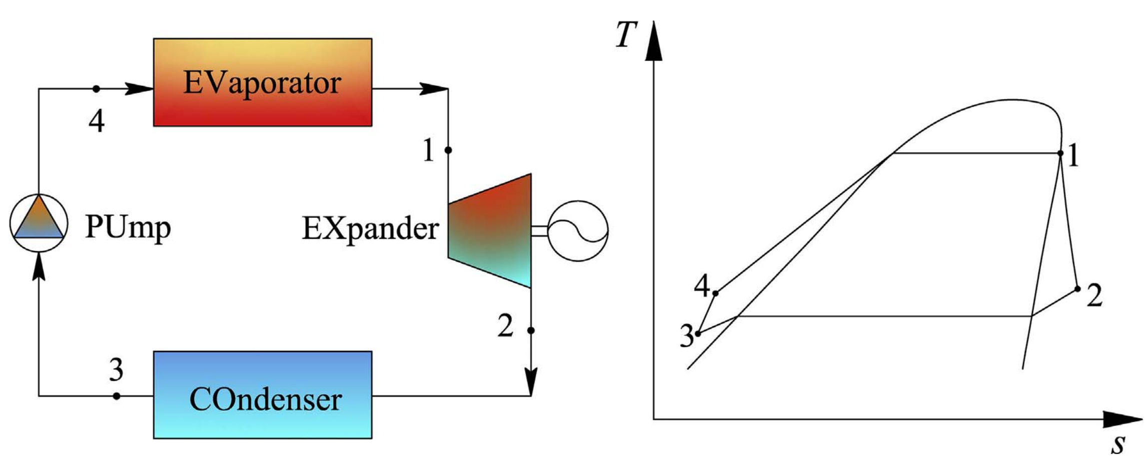

Fig. 1. ORC and its *T-s* diagram.