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Effect of off-design heat source temperature on heat transfer characteristics and system performance of a 250-kW organic Rankine cycle system

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HIGHLIGHTS

- An off-design operation of an organic Rankine cycle system was studied.
- The evaporation temperature increases as heat source temperature increases.
- Higher heat source temperature yields better preheater heat transfer performance.
- A smaller evaporator's heat capacity for a higher heat source temperature.
- The system performance is improved by increasing heat source temperature.

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ABSTRACT

This work investigated the effect of off-design heat source temperature on the heat transfer characteristics and system performance of a 250-kW organic Rankine cycle system. R245fa was used as a working fluid. The net power output was 243 kW and the system thermal efficiency was 9.5% under design conditions. For an off-design heat source temperature ($T_{W,\text{in}}$), the operating pressure was controlled to meet that R245fa reached the saturation liquid and vapor states at the outlet of the preheater and evaporator, respectively. The results demonstrated that the increase rate in evaporation temperature was almost the same as that in $T_{W,\text{in}}$; higher $T_{W,\text{in}}$ yields better heat transfer performance of the preheater and required a smaller evaporator heat capacity; and the net power output and system thermal efficiency increased linearly with increasing $T_{W,\text{in}}$. The net power output increased by 41.9%, whereas the total heat transfer rate increased by only 7.0% for the studied range of $T_{W,\text{in}}$. In conclusion, an off-design operation was studied by the pressure control approach within a heat source temperature variation of −10.3 °C to +19.8 °C from design, resulting in variations of −13.6% to +22.6% and −11.5% to +17.4% in the net power output and system thermal efficiency, respectively.

1. Introduction

Operation of an organic Rankine cycle (ORC) is based on the same principles as that of a steam Rankine cycle but differs from the latter in its usage of low-boiling-point organic fluids as a working fluid, which enables power generation at low heat source temperatures [1]. The ORC is considered to be one of the most economic and efficient ways to convert thermal energies of the low grade type, such as geothermal energy, solar thermal energy, waste heat recovery, biomass energy, and ocean thermal energy, to electricity [2]. Recently, ORCs have been studied from several viewpoints, such as technical and economical surveys of markets [1,3], selection of working fluids [4–6], proof of concept demonstrations [7,8], optimal control strategy modeling [9], quasi-dynamic models [10], and prototype testing [11,12].

Because the ORC system is based on the heat-to-power conversion process, the heat exchange system becomes a very important component. Moreover, an evaporation temperature, related to the working fluid's flow rate and the specific enthalpy change, is a crucial parameter in the ORC system. Li et al. [13] have explored the effect of the evaporation temperature on the system thermal and exergy efficiencies and its effect on the net power output of the ORC system. Their study results demonstrate that the system exergy efficiency and the net power output both increase with an increase

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in the evaporation temperature. The pinch point temperature difference of the heat exchange system, being an additional important parameter, also significantly influences the performance of the ORC system. Li et al. [14] found that under their studied system conditions, the best pinch point temperature difference of the evaporator was about 13 °C whereas the pinch point temperature of the condenser was about 17 °C. Different organic working fluids achieved maximal net power output per heat transfer area at nearly the same pinch point temperature of the evaporator. In addition, these authors also demonstrated that the optimal pinch point temperature difference of the evaporator decreases with a decrease in the pinch point temperature of the condenser.

Although there have been many studies concerning the effect of a number of system parameters on the ORC system performance [2,5,9,13–18], a detailed analysis of the effect of heat source temperature on heat transfer characteristics and system performance has rarely been performed. In this work, we analyzed the heat transfer characteristics and system performance of a 250-kW ORC system at off-design heat source temperatures by the pressure control approach, i.e., changing the evaporating pressure to meet the particular system requirements when the heat source temperature varies from the design value. Such the pressure control approach is different from the previous study of Roy et al. [15], which explored the performance analysis of the ORC with superheating for two different heat source temperature conditions at a constant turbine inlet pressure of 2.50 MPa, indicating the constant evaporating pressure. In their study, these two different heat source temperature conditions were: (1) the temperature of the heat source was kept constant of 550 K and (2) the difference between the heat source temperature and turbine inlet temperature was kept constant of 15 K. In addition, we also examined the evaporation temperature and pinch point temperature difference for off-design heat source temperatures of the present system.

2. ORC system

The studied ORC system is shown schematically in Fig. 1. The system consists of pump, preheater (shell-and-tube type), evaporator (flooded and shell-and-tube type), turbine, generator, condenser (flooded and shell-and-tube type), hot water (supplied by the boiler with a maximal capacity of 3788 kW), and cooling water (supplied by the cooling tower with a maximal capacity of 1000 RT, i.e., 3860 kW) circulation systems. The preheater design parameters are listed in table 1. In this study, enhanced factors of 1.6 and 1.2 were employed for estimating the heat transfer coefficients on the shell and tube sides, respectively, of the preheater [19]. The refrigerant R245fa was used as a working fluid; this refrigerant is one of the most suitable fluids for the low-grade waste heat recovery of the ORC system [20]. The mass flowrate was set to 11.58 kg/s. The working fluid R245fa flowed in the shells of the heat exchangers, whereas hot and cooling water flowed in the tube. The construction of this ORC prototype, whose engineering drawing is shown in Fig. 2, is underway at the Industrial Technology Research Institute, Taiwan.

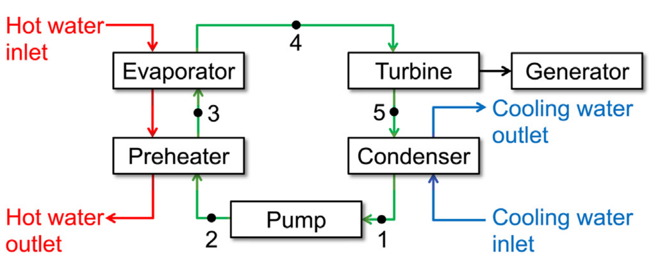

Fig. 1. Schematic presentation of ORC system under study.

Table 1
Detailed parameters of the designed preheater.

Tube inner/outer diameter	1.471/1.587 cm
Tube thickness	0.058 cm
Tube number	200
Tube in window	83
Tube bundle	1 pass
Tube inner type	Rifled
Tube outer type/Fin per inch (FPI)	Low-finned/42
Tube arrangement	Staggered
Tube pitch transverse	1.984 cm
Tube pitch longitudinal	1.718 cm
Tube/Shell length	360 cm
Shell inner diameter	32.45 cm
Bundle hole diameter	1.61 cm
Bundle diameter	31.66 cm
Sealing strips number	0
Nozzle inner diameter	10 cm
Baffle plate diameter	31.95 cm
Baffle thickness	0.4 cm
Baffle spacing	20 cm
Baffle cut	30%
Baffle plate number	17
Tube side enhanced factor	1.2
Shell side enhanced factor	1.6

Fig. 3 shows the T-s diagram of the present ORC system. The design operating pressures in the preheater/evaporator and in the condenser were 1.265 MPa (evaporation/saturation temperature was 100 °C) and 0.242 MPa (condensation temperature was 39 °C), respectively. The design points of the heat source (hot water) temperature ($T_{W,in}$) and the mass flowrate ($\dot{m}_W$) were 133.9 °C and 15.39 kg/s, respectively. Under these design conditions, the net power output was 243 kW and the system thermal efficiency was 9.5%. The analyzed heat source temperature ranged from 123.6 °C to 153.7 °C.

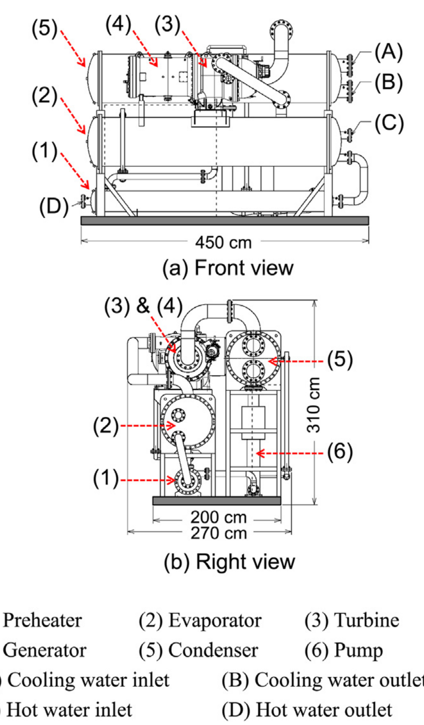

Fig. 2. Engineering drawing of the ORC prototype: (a) Front view and (b) right view.