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Investigation on the optimal condensation temperature of supercritical organic Rankine cycle systems considering meteorological parameters

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ABSTRACT

Organic Rankine cycle (ORC) system is one of the important technologies for waste heat utilization with mid-to-low temperatures. Compared to the steam Rankine cycle (SRC) system, the fluctuation of the condensation temperature due to seasonal and meteorological factors has a more significant effect on the performance of ORC systems since the temperature difference between evaporation and condensation is relatively smaller. In this paper, supercritical ORC thermodynamic models under design and off-design conditions are established. The condenser is divided into pre-cooling section and condensation section. The simulation results show that the net output power and thermal efficiency decrease with the rise of cooling water inlet temperature in the condenser. It is found that the effect of higher and lower cooling water inlet temperature compared to the design condition on the system performance is asymmetric. In addition, considering the meteorological parameters, the optimal design condensation temperatures of ORC system in Beijing, Shanghai and Guangzhou are about 30–34 °C, 34–38 °C and 38–42 °C individually. Present results on the suitable design condensation temperature can provide reference for the practical application and optimization of ORC systems.

1. Introduction

In recent years, with the consumption of social resources and deterioration of living environment, recovery of low temperature waste heat is attached great importance. Organic Rankine cycle (ORC) is considered as one of the promising technologies for low temperature waste heat utilization. As an emerging technical means, the ORC system performance [1–3], equipment parameter optimization [4–6], the choice of working fluid [7–10], and dynamic prediction and control strategy [11–13] are the current research hotspots. Compared to the steam Rankine cycle (SRC), the change of the condensation temperature of ORC system has a more obvious effect on the stability of the system performance because the temperature difference between evaporation and condensation is much smaller [14,15]. For SRC such a temperature difference could be as high as 550 °C. But for ORC, generally it is around 100–250 °C. Therefore, fluctuation of condensation temperature due to environmental factor plays a key role. However, its effect was rarely studied up to now.

There are studies focused on the effects of subcooling degree in the condenser, pinch temperature difference, and condensation temperature on the system performance of ORC. Li et al. [16] regarded ORC electric power cost (EPC) as the optimization goal, and proposed that with the increase in the pinch point temperature difference of the condenser, the EPC dropped first and then rose. Feng et al. [17] compared the effects of evaporation temperature, condensation temperature, pinch point temperature difference and superheat degree on the cycle performance of pure and mixture working fluids by establishing thermodynamic model. Li [18,19] pointed that the thermal efficiency of ORC system increased with the decrease of the condensation temperature and decreased with the decrease of the evaporation temperature. When the condensation temperature and the evaporation pressure were constant, the thermal efficiency increased with critical temperature of the working fluid. Samer et al. [20] pointed that the latent heat of vapor steam in the wet flue gas can be recovered by a condensing unit. Cold water was heated into steam by flue gas through direct contact water vapor condensation recovery in the condensing unit and then flowed into evaporator to transfer heat to working fluid. The net turbine power was maximized when the water temperature was close to the wet-bulb temperature of the flue gas. The pinch temperature of direct contact heat exchanger was as low as 0.5 K. Suresh et al. [21] pointed that the energy and exergy efficiencies decreased with condensation pressure increasing because of a lower enthalpy drop in the expander and exergy destruction in the condenser.

Some investigations were carried out to compare the different thermal performance of pure and mixture working fluids. Liu et al. [22–24] used zeotropic mixtures as the working fluid, optimized the

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Nomenclature

Cp	specific heat (kJ/kg °C)
d	diameter (m)
F	heat transfer area (m^2)
g	gravitational acceleration (m/s^2)
h	specific enthalpy (kJ/kg)
H	lift of pump (m)
K	total heat transfer coefficient ($W/(m^2 K)$)
L	fin height (m)
m	mass flow rate (kg/s)
p	pressure (MPa)
p_b	back pressure (MPa)
Pr	Prandtl number
Q	quantity of heat (kW)
r	dirt resistance ($(m^2 K)/W$)
Re	Reynolds number
T	temperature (°C)
ΔT	difference of temperature (°C)
v	specific volume (m^3/kg)
V	volume flow rate (m^3/h)
W	work (kW)
Y	fin pitch (m)

Greek symbols

α	heat transfer coefficient ($W/(m^2 K)$)
λ	heat conductivity coefficient ($W/(m K)$)
ρ	density (kg/m^3)
μ	dynamic viscosity ($kg/(m s)$)
η	efficiency
η_m	mechanical efficiency

Subscripts

c	condenser
co	cooling water
co1	inlet of cooling water in condensation section
co2	inlet of cooling water in pre-cooling section
co3	outlet of cooling water in pre-cooling section
cp	pinch point of condenser
e	evaporator
ep	pinch point of evaporator
es	equivalent value
ex	expander
f	working fluid
fm	the average value of working fluid
g	generator
he	heat resource
he1	inlet of heat source in evaporator
he3	outlet of heat source in evaporator
hp	pinch point of evaporator
i	inside the tube
m	average value
net	net value
pc	cooling water pump
pf	working fluid pump
s	isentropic value
vc	constant-volume compression
ve	constant-volume expansion
w	wall
0	outside the tube
0a	outside the tube in pre-cooling section
0b	outside the tube in condensation section
1–5	state point

components of mixtures, and then analyzed the effect of temperature slip on the ORC system performance and proposed the method of determining the optimal condensation pressure. Andreasen et al. [25] presented that when the temperature glide of condensation matched the temperature increase of the cooling water, the net power would maximize for some mixture fluids. Ghim et al. [26] studied condensing heat transfer coefficients of two pure ORC working fluids, R245fa, n-pentane and their mixtures (91.2% n-pentane and 8.8% R245fa) via experimental investigation. Sebastian et al. [27] used R1233zd-E, R245fa as the working fluids, due to the higher volume flow of R1233zd-E in the condenser, the mean overall heat transfer coefficient and pressure drop were higher than those of R245fa.

A few of studies considered the effects of ambient temperature, and proposed new types of the condenser and condensation method. Erhart et al. [28] observed the characteristics of condenser in ORC system for winter and summer operation, due to variable condensation temperatures and pressure levels, the difference in the electric yield of the cycle was about 10%. Quoilin et al. [29] studied the effect of ambient temperature on the solar ORC system. When the ambient temperature increased from 2 °C to 30 °C, the efficiency of ORC system decreased by 15% and the total efficiency of power generation system decreased by 13%. Through simulation and experiment, Miao et al. [30] proposed that the ambient temperature and humidity affected the system performance. At high ambient temperatures, the effect of humidity became significant. During the summer, when the humidity increased from 50% to 90%, the expander output could be reduced by one third. Li et al. [31] pointed out that the condensed liquid separation method can increase the heat transfer coefficient by 23.8%, reducing the heat transfer area of the condenser by 44.1%. Zhou et al. [32] proposed a dual-loop system for the recovery of waste heat. The mixtures in the low temperature loop had a better system performance than the pure fluids because of better temperature matching during the condensation process. It was shown that the suitable mixture not only increased the thermal efficiency, but also absorbed more heat in the low temperature loop. Chen et al. [33] investigated liquid-vapor separation condenser (LSC), and proved that it had a better thermodynamic performance than a common parallel flow condenser (PFC) with the identical structure of tube and fin.

The literature listed above mainly attached importance to the impact of the condenser section on ORC system, but rarely studied the value of optimal condensation temperature. Therefore, the main objective of this paper is to study the influence of the variable cooling water inlet temperatures on the system performance so as to determine the optimal design condensation temperature. The system performance includes energy and exergy [18,21] performance, by establishing a thermodynamic model, net output power and thermal efficiency are used as evaluation criteria for system performance in this paper. The relationship between the cooling water inlet temperature and the condensation temperature can be obtained by the heat exchanger model. In this paper, the water is cooled by air in a cooling tower, it is indispensable to pay attention to changes in meteorological parameters. Taking Beijing, Shanghai and Guangzhou as examples, the net output power of ORC system under the design and off-design conditions are obtained according to the system modeling and thermodynamics calculation. Then, the annual net output powers based on the meteorological parameters are calculated. After the evaporation temperature is optimized and fixed, the condensation temperature corresponding to the maximum annual net output power and close to it within a certain range are considered as the optimal design condensation temperatures for the system. Since the supercritical ORC system is superior to the subcritical in given conditions, the thermodynamic calculation in this paper is based on the supercritical cycle.