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Parametric design and off-design analysis of organic Rankine cycle (ORC) system

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ABSTRACT

A one-dimensional analysis method has been proposed for the organic Rankine cycle (ORC) system in this paper. The method contains two main parts: a one-dimensional aerodynamic analysis model of the radial-inflow turbine and a performance prediction model of the heat exchanger. Based on the present method, an ORC system for the industrial waste heat recovery is designed and analyzed. The net power output of the ORC system is 534 kW, and the thermal efficiency reaches 13.5%. System performance under off-design conditions is simulated and considered. The results show that the inlet temperatures of the heat source and the cooling water have a significant influence on the system. With the increment of the heat source inlet temperature, the mass flow rate of the working fluid, the net power output and the heat utilization ratio of the ORC system increase. While, the system thermal efficiency decreases with increasing cooling water inlet temperature. In order to maintain the condensation pressure at a moderate value, the heat source inlet temperature considered in this analysis should be kept within the range of 443.15–468.15 K, while the optimal temperature range of the cooling water is between 283.15 K and 303.15 K.

1. Introduction

With the development of human society, the energy demand is enlarging rapidly, which results in growing consumption of primary fossil fuels and massive discharge of pollutants. Consequently, the energy shortage and the environmental deterioration are the crucial issues that the developing world must face. With intense concerns for energy conservation and emission reduction, the utilization of the low-grade heat sources has attracted enormous attention in recent years. Among all of the existing technologies, organic Rankine cycle (ORC) has been proven to be an effective solution to utilize the low-temperature energies, including solar energy [1,2], geothermal energy [3,4], biomass energy [5,6] and industrial waste heat [7,8]. A large number of researches have been conducted on ORC systems, including working fluid selection and system design and optimization. Hung [9], Borsukiewicz-Gozdur and Nowak [10] and Saleh et al. [11] studied working fluid selection for low-temperature ORC systems, with the net power output and the system thermal efficiency as the criteria. Song and Gu [12], Zhang et al. [13] and Feng et al. [14] compared the thermal performance of the ORC system with pure and mixture working fluids. As for the ORC system design, different schemes have been presented and studied, such as simple systems [15,16], regenerative systems [16,17], preheated systems [18,19] and dual-loop systems [20,21]. Thermal performance, technological feasibility and economic aspects are considered in ORC system optimization [22–24].

In previous studies, the design condition is mainly concerned for the ORC system. However, the operating condition of the ORC system will change markedly with the heat source and the cooling source. Therefore, performance of the ORC system under off-design conditions is also important and should be considered in the design and optimization process. The ORC system performance is evidently influenced by the components, mainly referring to the organic expander and the heat exchangers. As one of the key components, the organic expander plays a significant role in the ORC system. The radial-inflow turbine is typically selected for organic vapor expansion and power output. The performance prediction of the radial-inflow turbine is essential for ORC system analysis. In conventional performance prediction for turbomachinery, one-dimensional methods and through-flow analysis are two effective ways [25–27]. Based on NASA researches, Banies [28] modified the loss models and developed the mean-streamline method for radial-inflow turbines. A turbine analysis method was established for both design and off-design performance prediction;

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Nomenclature

W	power, kW
$\dot{m}$	mass flow rate, kg/s
h	specific enthalpy, kJ/kg
Q	heat load, kW
c_p	specific heat capacity, kJ/kg K
T	temperature, K
P	pressure, kPa
k	loss coefficient
c	absolute velocity, m/s
w	relative velocity, m/s
u	peripheral velocity, m/s
ρ	density, kg/m^3
A	area, m^2
K	heat transfer coefficient, W/m^2 K

Greek symbols

η	efficiency
ζ	loss
φ	nozzle velocity coefficient
ψ	rotor blade velocity coefficient
α	absolute flow angle
β	relative flow angle

Superscripts

$*$	total

Subscripts

wf	working fluid
HS	heat source
in	inlet
out	outlet
pump	pump
evap	evaporator
exp	expander
cond	condenser
c	cooling water
net	net
the	thermal
utilization	heat utilization
S	stator
R	rotor
id	ideal
is	isentropic
r	radial
ax	axial
HT	high temperature
LT	low temperature
max	maximum
min	minimum

Acronyms

ORC	organic Rankine cycle
CFD	computational fluid dynamics
GWP	global warming potential
ODP	ozone depletion potential
NTU	number of transfer unit

experimental data and numerical simulation results of a high expansion ratio radial-inflow turbine were used to validate the analysis method [29]. Binder et al. [30] presented a one-dimensional aerodynamic analytical method for radial-inflow turbine performance prediction under various conditions, which selected the load coefficient, mass flow coefficient and expansion ratio as the key parameters. Qiu and Baines [31] researched the flow in a high expansion ratio radial-inflow turbine in detail. The turbine performance was analyzed and compared with the CFD simulation results [32]. As for the heat exchangers, they determine the heat load absorbed by the ORC system and that rejected to the environment. The performance of the heat exchangers is evidently affected by the conditions of the heat and cooling sources.

This paper presents an analysis method for the ORC system, taking the one-dimensional aerodynamic analysis model of the radial-inflow turbine and the performance prediction model of the heat exchangers into account. As for a 500 kW level ORC system for waste heat recovery, parametric design is carried out, including working fluid selection and system parameter determination. Based on the analysis method for the ORC system, off-design analysis is conducted in detail. The influence of the heat source and the cooling water conditions on the system performance is evaluated.

2. ORC system

2.1. Thermodynamic model

Fig. 1 shows the schematic diagram of a basic ORC system. A basic ORC system consists of a working fluid pump, an evaporator, an organic expander and a condenser. Similar with the conventional steam Rankine cycle, the liquid organic working fluid from the condenser is firstly pumped to a high pressure state. Then in the evaporator, the organic working fluid is heated by the heat source and converted into saturated or superheated vapor. Next, the organic vapor expands in the expander to produce power. Finally, the exhaust organic gas from the expander is condensed to liquid again by the cooling water.

The T–s diagram of ORC is shown in Fig. 2, the thermal process of which can be described as follows.

Process 1 to 2 in the working fluid pump is given by

$$W_{pump} = \frac{\dot{m}_{wf} \cdot (h_{2s} - h_1)}{\eta_{pump}} \tag{1}$$

where h_{2s} is the isentropic enthalpy of the working fluid after being compressed in the pump, and η_{pump} is the efficiency of the pump.

Process 2 to 4 in the evaporator is given by

$$Q_{evap} = \dot{m}_{wf} \cdot (h_4 - h_2) = \dot{m}_{HS} \cdot c_{p,HS} \cdot (T_{HS,in} - T_{HS,out}) \tag{2}$$

where $c_{p,HS}$ is the average specific heat capacity of the heat source, and $T_{HS,in}$ and $T_{HS,out}$ are defined as its inlet and outlet temperatures, respectively.

Process 4 to 5 in the organic expander is given by

$$W_{exp} = \dot{m}_{wf} \cdot (h_4 - h_{5s}) \cdot \eta_{exp} \tag{3}$$

where h_{5s} is the isentropic enthalpy of the exhaust organic gas at the expander outlet, and η_{exp} is the efficiency of the organic expander.

Process 5 to 1 in the condenser is given by

$$Q_{cond} = \dot{m}_{wf} \cdot (h_5 - h_1) = \dot{m}_c \cdot c_{p,c} \cdot (T_{c,out} - T_{c,in}) \tag{4}$$

where $c_{p,c}$ is the average specific heat capacity of the cooling water, $T_{c,in}$ and $T_{c,out}$ are its inlet and outlet temperatures, respectively.