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Research Paper

A novel comprehensive evaluation methodology of organic Rankine cycle for parameters design and working fluid selection

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HIGHLIGHTS

- An evaluation system from thermodynamics, economy and environment is constructed.
- A CEM using entropy theory and gray relational method is presented.
- A comprehensive evaluation indicator based on HRE, IEE, PBP and AER is provided.
- The overall performance under different parameters and working fluid is evaluated.

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ABSTRACT

In order to improve the overall performance of organic Rankine cycle (ORC) systems, a novel evaluation method using the combination of grey relational method and entropy theory was presented. Based on a comprehensive evaluation indicator, which is constituted by 4 indicators in terms of thermodynamics, economy and environment, system performance was evaluated under different turbine inlet pressure and pinch point temperature difference. Besides, a performance comparison of six different working fluids was conducted. The results show that ORC system can achieve a better comprehensive performance at lower pinch point temperature difference in the evaporator. And there is an optimal turbine inlet pressure, which is significantly influenced by the inlet temperature of exhaust gas, to minimize the value of comprehensive evaluation index (CEI). As a low global warming potential (GWP) working fluid, butane produces the best comprehensive performance for exhaust temperature range of 443–483 K, and R1233zd(E) gives the highest value of CEI in exhaust temperature range of 483–513 K. Additionally, R1234yf is recommended for exhaust temperature lower than 443 K.

1. Introduction

The shortage of the energy and global warming promote the development of utilization of low-grade waste heat, which is widely distributed in different industrial fields and accounts for more than half of the total generated heat [1]. Among various thermodynamic cycles for waste heat recovery, such as organic Rankine cycle (ORC) [2,3], Kalina cycle [4], supercritical CO_2 cycle [5], triangle cycle [6] and so on, ORC is a very potential candidate because of its high efficiency, reliability and flexibility [7].

Extensive research has been performed on ORC systems, which mainly focuses on working fluid selection [8,9], the improvement of system configurations [10,11] and parameters optimization [12,13]. Actually, a reasonable and comprehensive evaluation criterion plays a critical role in finding the optimal parameters and working fluids. Currently, the main evaluation criterion of an ORC is constructed from three aspects, including thermal performance, economical characteristic and environmental impact.

For the thermal performance evaluation of ORC systems, Hærvig et al. [14] conducted a thermodynamic analysis to provide general guidelines for working fluid selection. Based on the net output power, the critical temperature of the optimum working fluid is approximately 30–50 K higher than hot source temperature. In order to select the most appropriate ORC layout, recuperated cycles, superheated cycles, supercritical cycles, regenerative cycles and their combinations were compared and analyzed by Lisa et al. [15]. Main target indexes concerned consisted of cycle efficiency, specific work, recovery efficiency, turbine volumetric expansion ratio, ORC fluid-to-hot source mass flow ratio and heat exchangers size parameter. Dai et al. [16] optimized the inlet temperature and pressure of turbine for an ORC system by using exergy

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Nomenclature

CEI	comprehensive evaluation index
HRE	heat recovery efficiency
PBP	payback period
TIP	turbine inlet pressure
Q	heat flow rate, W
c	specific heat, $kJ \cdot kg^{-1} \cdot K^{-1}$
T	temperature, K
K	heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
R	thermal resistance, $W \cdot m^{-2} \cdot K^{-1}$
H	height, m
Y	fin pitch, m
d	diameter of tube, m
p	pressure, Pa
Δp	pressure drop, Pa
W	power, kW
C	cost,$
t	time, h
w	weight coefficient
N_c	number of channels
S_{lt}	lifetime, year
P_{CO}	corrugation pitch, m

Greek

η	efficiency, %
δ	thickness, m
μ	viscosity, Pa·s
ρ	density, $kg \cdot m^{-3}$
ζ	friction factor

Superscripts

g	exhaust gas
c	condenser
in	inside
t	turbine
cw	cooling water
gen	generator
pri	price
pp	pinch point

Superscripts

′	saturation liquid
r	reduction
CEMM	comprehensive evaluation methodology
IEE	internal exergy efficiency
AER	annual emission reduction
PPTD	pinch point temperature difference
m	mass flow rate, $kg \cdot s^{-1}$
h	specific enthalpy, $J \cdot kg^{-1}$
A	heat transfer surface area, m^2
ΔT	temperature difference, K
E	exergy, W
Re	Reynolds number
Nu	Nusselt number
Pr	Prandtl number
x	vapor quality
υ	velocity, $m \cdot s^{-1}$
G	mass flux, $kg \cdot m^{-2} \cdot s^{-1}$
L	length, m
CF	conversion factor
D_h	hydraulic diameter, m
b	plate spacing, m
r	correlation coefficient
α	heat transfer coefficient, $W \cdot m^{-2} \cdot K^{-1}$
λ	thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
β	chevron angel, degree
Ω	distinguish coefficient
e	evaporator
f	working fluid
o	outside
p	pump
s	isentropic
op	operation
om	operation and management
″	saturation vapor
em	emission

efficiency as the evaluation criterion. Zhang et al. [17] provided the optimum cycle layout and operation parameters simultaneously according to different indicators. The concerned thermal indexes included thermal efficiency, exergy efficiency and recovery efficiency. In addition, Shu et al. [18] conducted a comprehensive analysis of ORC systems based on the multi-approach evaluation system. The screening criteria included net power, thermal efficiency, exergy loss, exergy efficiency, electricity production cost and depreciation payback period.

As to the economic evaluation of ORC systems, Wang et al. [18] carried out an economic analysis for a subcritical ORC system. The investigation showed that payback period decreased with the increase of flue gas temperature and mass flow rate. Based on the average cost of electricity, Barse et al. [19] studied the effect of working fluids on the economic performance of the system and recommended R236ea. Li et al. [20] presented a thermo-economic analysis and comparison of a CO_2 transcritical power cycle and an ORC. The cost of the net output power per unit and the cost ratio of the heat exchanger to the overall system were considered as the economic indicators. Walraven et al. [21] performed an optimization of cycle parameters and heat exchanger geometry for an ORC. The study aimed at finding an economic configuration which could provide the highest net present value for the ORC.

As to the environmental impact of ORC systems, the emissions of green gas, such as CO_2, SO_2, and NOx, was employed as an indicator by Wang et al. [22]. In a research, Liu et al. [23] conducted an environmental evaluation using the life cycle assessment method. Environmental indexes like global warming potential (GWP), acidification potential, solid waste potential, human toxicity potential, eutrophication potential as well as dust potential have been investigated. Ahmadi et al. [24] performed a comprehensive exergo-environmental analysis of a trigeneration system integrated with an ORC. A sustainability index and CO_2 emissions were selected to evaluate the environmental impacts.

As a sustainable system, ORC system should be evaluated from thermodynamics, economy and environment, etc. Therefore, a comprehensive evaluation that combines all important criteria into one comprehensive indicator is of great importance to the ORC system. Grey relational method combines the values of different indicators into a quantified value of grey relational grade, which provides a possible approach to the multi-criteria analysis of ORC systems. The method has been successfully applied to the performance evaluation of the cogeneration system [25] and ORC systems [26]. However, the evaluation results depend greatly on the weight coefficient of different indicators.

Previous investigations as reviewed above are mostly not comprehensive enough to cover all these important aspects of the ORC system