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Multi-objective optimisation and fast decision-making method for working fluid selection in organic Rankine cycle with low-temperature waste heat source in industry

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ABSTRACT

In China, the utilisation of low-temperature waste heat (especially at temperatures lower than 100 °C) plays a significant role in increasing the energy-consumption efficiency in the industry. The organic Rankine cycle (ORC) is considered as a promising method to recover the aforementioned part of the waste heat. In the study, six potential candidates, namely R141b, R142b, R245ca, R245fa, R600a, and R601a were screened from 12 dry or adiabatic organic working fluids based on their thermodynamic performances in the ORC. A multi-objective optimisation (MOO) was performed for the thermodynamic performance (exergy efficiency, EXE) and economic performance (levelised energy cost, LEC) by using non-dominated sorting genetic algorithm-II (NSGA-II). The Pareto frontiers were obtained for the six candidates with the algorithm, and each optimal compromise solution was accurately obtained with the fuzzy set theory. Based on the EXE and LEC of the optimal compromise solution, the total cost and power generation efficiency for the six candidates were determined. This was used to obtain an explicit evaluation index in economic performance, namely static investment payback period (SIPP), to identify that the R245ca corresponded to the most cost-effective working fluid with the shortest SIPP. This suggests R245ca was the fastest to cover the investment and cost of the ORC system. Furthermore, a fast decision-making method was introduced to select the optimal working fluid based on the grey relational analysis (GRA) by considering key physical property parameters of the working fluids. The results suggest that any potential working fluid to recover low-temperature waste heat in the ORC can be evaluated by the simplified grey relational degree (SGRD) proposed in the study.

1. Introduction

Industry in China accounts for approximately 68% of total energy consumption and the energy consumed for unit industrial product is 30% higher than that at the international level [1]. As widely-known, most of the waste heat produced in industrial processes can be recycled with immense potential for energy conservation [2]. The waste heat is generally classified into high-temperature (> 650 °C), medium-temperature (230–650 °C), and low-temperature (< 230 °C) waste heat [3]. The recovery techniques for high- and medium-temperature waste heat are well developed. For example, high-temperature (1000 °C) sensible heat of hot coke is recovered by coke dry quenching (CDQ) technology, and medium-temperature (350 °C) exhaust gas from a kiln hood clinker cooler and kiln tail preheater is captured with a boiler to exchange heat with water. However, only a few efficient technologies are recognised to recover low-temperature waste heat, and their proportion exceeds 30% of the total waste heat in the industry because low exergy leads to a low efficiency of recovery. However, there are several methods to achieve the aforementioned objective including the organic Rankine cycle (ORC), trilateral cycle [4–6], and Kalina cycle [7–9]. It should be noted that a recovery technique for low-temperature waste heat should not be hindered by low conversion efficiency because the cost of the waste heat may be negligible. A reasonable payback period that is determined by the investment and profit should be employed as an evaluation criterion for an appropriate recovery technique. Given the advantages of compact structure, easy operation, and high efficiency when compared with alternative methods, ORC is considered as a promising method and is widely employed to convert low-grade heat resources to electricity in the domain of low-temperature waste heat recovery.

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Nomenclature

Symbols

A	heat transfer area, m^2
a	thermal diffusion rate, m^2/s
B	characteristic number of boiling
C	purchased cost
d	diameter of tube, m
E	exergy flow rate, kW
e	specific exergy, kJ/kg
F	non-dimensional coefficient
G	mass flux, $kg/(m^2{\cdot}s)$
g	gravitational acceleration, m/s^2
h	specific enthalpy, kJ/kg
I	exergy loss rate, kW
K	total heat transfer coefficient, $W/(m^2{\cdot}K)$
m	mass flow rate, kg/s
Nu	Nusselt number
P	price, USD
Pr	Prandtl number
Q	heat transfer rate, kW
q	heat flux, W/m^2
R	revenue, USD
Re	Reynolds number
r	relational degree
s	specific entropy, kJ/(kg·K)
T	temperature, K
t	time, h
u	dynamic viscosity, $(N{\cdot}s)/m^2$
v	velocity of the fluid, m/s
W	power, kW
w	weight
x	sequence
X	set of sequence

Greeks

α	heat transfer coefficient, $W/(m^2{\cdot}K)$
γ	the latent heat of vaporisation, kJ/kg
Δ	difference
δ	thickness, m
η	efficiency, %
λ	thermal conductivity, W/(m·K)
μ	member value of each solution
ξ	number of objective function
ρ	density, kg/m^3
υ	kinematic viscosity, m^2/s
ψ	objective function
ω	decision-making weight

Abbreviations

CDQ	coke dry quenching
CEPCI	chemical engineering plant cost index
CFC	chlorofluorocarbon
CRF	capital recovery factor
EXE	exergy efficiency
GRA	grey relational analysis
HCFC	chlorodifuoromethane
HFC	hydrofluorocarbon
LEC	levelised energy cost
LINMAP	linear programming techniques for multidimensional analysis of preference
LMTD	logarithmic mean temperature difference
MOO	multi-objective optimisation
NIST	National Institute of Standards and Technology
NSGA	non-dominated sorting genetic algorithm
ORC	organic Rankine cycle
PPTD	pinch point temperature differences
SGRA	simplified grey relational analysis
SGRD	simplified grey relational degree
SIPP	static investment payback period
TISCO	Taiyuan Iron & Steel CO., LTD
TOPSIS	technique for order preference by similarity to an ideal solution
UGO	universal global optimisation
USD	United States dollar

Subscripts

1–16, 2s, 6s	state points
ave	average
bm, X	bare module
con	condenser
cs	cooling source
ele	electricity
eva	evaporator
exe	exergy
hi	heat source inlet
ho	heat source outlet
hr	hour
hs	heat source
in	inner
k	number of Pareto optimal solution
l	liquid
max	maximum
mch	mechanical
min	minimum
net	net
ohd	overheat degree
om	operation and maintenance
op	operation
out	outer
pg	power generation
p, X	purchased
pum	pump
sys	system
tot	total
tur	turbine
ucd	undercooling degree
v	vapour
wall	tube wall
wf	working fluid

A matter of significant concern is that a few specific relationships exist between the working fluid selection and cost of investment while recovering the waste heat by the ORC. This is because the physical property parameters of a working fluid to a certain extent determine the capital cost of the primary equipment including the evaporator, turbine, condenser, and pump. Therefore, this should be considered as an evaluation factor in working fluid selection and especially for low-temperature waste heat recovery. Previous studies significantly focused on the working fluid selection. Hung [10] is one of the earliest scholars on the working fluids selection for the ORC who indicated that R113