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Cost-effectiveness performance analysis of organic Rankine cycle for low grade heat utilization coupling with operation condition

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HIGHLIGHTS

- A net power output model is proposed and compared with theoretical data.
- For fixed operation condition, low *Ja* fluid shows attractive performance in ORC.
- The heat source rather than working fluid determines ORC performance at low $T_{hs,in}$
- The peak W_{net} and best CEP cannot be achieved at the same time, compromise must be made.

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ABSTRACT

This paper analyzed the influence of working fluids selection and operation conditions on the cost-effectiveness performance and net power output of an ORC for low grade heat utilization. A net power output model has been proposed theoretically and compared with the theoretical data calculated from thermodynamic analysis, exhibiting excellent agreements with the theoretical data. The proposed net power output model theoretically indicates that Jacob number and the ratio of evaporating temperature and heat rejected temperature play essential roles in discriminating the net power output among various working fluids at the same operation condition. For a given condensing and evaporating temperature, it can be concluded theoretically that fluid with low Jacob number will show attractive performance in an ORC. The maximum net power output is determined by the heat source rather than working fluids with a low inlet temperature of heat source. Cost-effectiveness performance analysis reveals that the maximum net power output and the best CEP cannot be achieved at the same time and compromise must be made when choosing the most suitable organic working fluids in different ORC designs.

1. Introduction

About one-third of the heat supply in winter season was provided by natural gas boilers in Beijing (China). Unfortunately, the exhaust flue gas, with temperature of 370–570 K, is directly discharged into environment [1]. As China surveys the world, low grade heat such as geothermal, industrial waste heat and heat from low to moderate temperature solar collectors, accounts for more than one half of the total heat generated worldwide [2–4].

In the past decades, large attempts are made to extend the market share of renewable energy sources, extensive researches have been performed on converting low temperature heat ($353 < T < 573$ K) into electricity. Contrasted with the conventional steam Rankine cycle [5–8], organic Rankine cycle possesses the capability to convert low grade heat sources into electricity and has become a significant issue in power engineering and the number of published papers is rapidly increasing. The investigations on the ORC system can be summarized into the following sorts:

- Modification of the basic ORC for improving system efficiency.
- Selection of the suitable working fluids for different heat sources.
- Replacement of the pure working fluids with zeotropic mixture.
- Optimization of the ORC system.

Hung et al. [7], Maizza et al. [9,10], Liu et al. [11], Hung [12], Larjola [13], Srinivasan et al. [14] proposed and analyzed various ORCs designed for the waste heat recovery systems. Techanche et al. [15], Hung et al. [16] studied the application of ORCs in solar

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Nomenclature

h	enthalpy [kJ/kg]
v	specific volume [m^3/kg]
$\dot{m}$	mass flow rate [kg/s]
p	pressure [MPa]
$\dot{Q}$	heat rate [MW]
q	heat rate [W/kg]
s	entropy [kJ/kg K]
T	temperature [K]
$\dot{W}$	work [MW]
x	quality
c_p	specific heat [kJ/kg K]
h_f	fin height [mm]
s_f	fin pitch [mm]
L_f	fin length in serrated fin [mm]
d_f	plate spacing [mm]
ΔT_m	logarithmic mean temperature difference [K]
K	total heat transfer coefficient [W/m^2 K]
G	mass flow rate [kg/m^2 s]
d	hydraulic diameter [mm]
j	Colburn factor
A	heat transfer area [m^2]
F_p	heat transfer area in plate fin channel [m^2]
F_f	heat transfer area in finned plate channel [m^2]
Pr	Prant number
Re	Reynolds number
Nu	Nusselt number
Bo	Boiling number

Greek symbols

η_{th}	thermal efficiency [%]
η_{ex}	exergy efficiency [%]
γ	latent heat [kJ/kg]
μ	dynamic viscosity [Pa s]
ρ	density [kg/m^3]
δ_f	fin thickness [mm]
η_f	fin efficiency in finned plate channel
η_p	fin efficiency in plate fin channel
δ_c	thickness of clapboard [mm]
λ_c	thermal conductivity [W/m K]
α	heat transfer coefficient [W/m^2 K]

Subscripts

1–5	states in the cycle
hs	heat source
cs	cold source
bp	boiling point
c	condenser
crit	critical
pp	pinch point
ex	expander
e	evaporator
ev	evaporation
in	inlet
out	outlet
is	isentropic
g	generator
pu	pump
wf	working fluid
eq	equivalent
T	total
l	liquid
v	vapor
s	single-phase
t	two-phase
p	plate fin channel
f	finned plate channel

Acronyms

a	actual
s	ideal
RC	Rankine cycle
ORC	organic Rankine cycle
ALT	atmospheric life time
GWP	global warming potential
ODP	ozone depletion potential
PPTD	pinch point temperature difference [K]
CEP	cost-effectiveness performance [W/m^2]

organic Rankine cycle systems. Drescher et al. [17] proposed a method to find suitable thermodynamic fluids for ORC in biomass power and heat plants. Saleh et al. [18] analyzed the thermodynamic performances of alkanes, fluorinated alkanes, ether and fluorinated ethers as working fluids in ORCs for geothermal power plants. Hung et al. [16] studied the system efficiency of ORC using ocean thermal energy conversion (OTEC) system as heat sources. Schuster et al. [19] investigated the efficiency optimization potential in supercritical organic Rankine cycle. In view of numerical simulations and experimental studies, Yamamoto et al. [20], Quoilin et al. [21] presented numerical simulation models of ORC and carried out experimental analysis, respectively. Wei et al. [22] and Quoilin et al. [23] proposed dynamic models of ORC using turbine and scroll expander, respectively and provided insight in transient conditions due to fluctuations of the heat parameters and load demand. Desai et al. [24] considered the process integration of ORC and reported that the basic ORC can be modified by incorporating both regeneration and turbine bleeding to improve its thermal efficiency. Kuo et al. [25] analyzed the system performance of a 50 kW ORC system subject to influence of various working fluids and proposed a dimensionless for quantitatively screening working fluid. Quoilin et al. [26] focused on the thermodynamic and economic optimization of a small scale ORC in waste heat recovery application. Meanwhile, Dai et al. [27] considered the exergy efficiency as an objective function to optimize the thermodynamic parameters of the ORC for each working fluid by means of the genetic algorithm. They found that the cycle has the best performance property with saturated vapor at the turbine inlet. Wang et al. [28] showed their interest in the working fluid selection of ORCs for engine waste heat recovery. The outcomes indicate that R11, R141b, R113 and R123 manifest slightly better thermodynamic performances than the others, while R245fa and R245ca are the most environment-friendly working fluids for engine waste heat-recovery applications.

The system performance of ORC is strongly related to the working fluid. Hence it is essential to carefully select the working fluid. No single physical property can be used as the sole indicator for quantitatively screening the working fluid [25]. Hung et al. [7] showed that the major physical property of screening the working fluid includes specific heat, latent heat and slope of saturation vapor curve. As shown in Fig. 1, working fluids can be classified into dry, isentropic or wet respectively in terms of the slope of saturation curve in T-s diagram to be positive, infinite or negative [5]. We confirmed that dry and isentropic fluids exhibit more desirable for