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Optimization of waste heat based organic Rankine cycle powered cascaded vapor compression-absorption refrigeration system

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ABSTRACT

In this paper, the thermo-economic optimization of the waste heat based organic Rankine cycle powered cascaded vapor compression-absorption refrigeration system is presented. Organic Rankine cycle with dry organic working fluid is used as a power generating cycle to provide input to the vapor compression refrigeration system. Moreover, the high temperature organic working fluid at the expander outlet is used to supply thermal need of the vapor absorption refrigeration system. The present system achieves low temperature cooling efficiently. However, initial capital cost and complexity are the practical limitations for the present system. The energetic efficiency of the present system for only cooling mode and cogeneration mode (cooling and heating) are calculated to be 22.3% and 79%, respectively. It may be noted that the extra heat available, apart from the thermal energy requirement of the vapor absorption system, is taken as process heat in the cogeneration mode. The simple payback period and break-even point are calculated (for the base case) to be 5.26 years and 4.22 years, respectively. The system size and annualized cost are optimized, using nonlinear programming based on conjugated directions method, to make the system potentially attractive for the industrial sector. Optimization results reveal that the annualized cost of the present system is decreased by about 12% compared to the base case. Moreover, the simple payback period and break-even point are reduced to 4.50 years and 3.48 years, respectively. The results of comparative economic study, between the present and stand-alone vapor compression refrigeration systems, show that the higher value of electricity price and the lower value of discount rate are favorable for the selection of the present system.

1. Introduction

Energy efficiency and energy conservation are gaining attention due to increase of greenhouse gas emissions and scarcity of fossil fuels. Waste heat released into the environment aggravates the environmental problems [1]. Apart from conventional steam Rankine cycle (SRC), the other power cycles for the waste heat recovery are organic Rankine cycle (ORC), Kalina cycle, single flash steam cycle, multi-pressure steam cycle, etc. [2]. ORC has received increasing attention during the last few years for utilizing low-medium temperature sources, like, waste heat, geothermal, biomass and solar thermal [3]. ORC is cited as a promising option for cogeneration, trigeneration, and multi-generation systems, which has higher energy utilization factor and efficiency. Use of organic refrigerants enable the system to reach lower evaporation temperature and dry expansion, which are beneficial for utilizing low grade heat and cogeneration [4]. ORC based cogeneration systems mainly use either vapor absorption refrigeration system (VARS) or vapor compression refrigeration system (VCRS) [5].

Efficient use of available energy sources and technological advancement propelled researchers to design integrated technologies based on combined heat and power (CHP), combine cooling and power (CCP), combine cooling and heating (CCH), trigeneration (combined cooling, heating and power), and multi-generation. Such integrated technologies allow simultaneous generation of utilities (e.g. heating, cooling, and/or power) using single energy source. Therefore, integrated systems offer high overall system efficiency and reduce the environmental problems [5]. Recent studies on ORC based cogeneration, trigeneration, and multi-generation systems are summarized in Table 1. Al-Sulaiman et al. [6] analyzed the ORC integrated vapor absorption refrigeration cycle using different energy sources and reported system efficiency about 76% for solid oxide fuel cell (SOFC), 90% for combined solar-biomass, and 46% for solar thermal with storage. Wang et al. [7] analyzed ORC integrated compression refrigeration cycle and reported overall COP of 0.54 (basic cycle), 0.63 (with sub-cooling) and 0.66 (with sub-cooling and recuperation). Al-Sulaiman et al. [8] analyzed biomass ORC integrated trigeneration system using absorption

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Nomenclature

A	area (m^2)
AC	annualized cost (USD/y)
a_i	regression coefficient
b_i	regression coefficient
C	capital cost (USD)
COP	coefficient of performance
c_p	specific heat capacity at constant pressure (kJ/(kg-K))
CRF	capital recovery factor (y^{-1})
D_i & D_O	internal and external tube diameter (m)
E	annual energy consumption (kWh/y)
f	operation and maintenance cost factor (%)
fr	friction factor
g	gravitational constant (m/s^2)
h	specific enthalpy (kJ/kg)
h_i & h_o	internal and external heat transfer coefficient (kW/m^2-K)
i	discount rate (*i*)
k	thermal conductivity (kW/m-K)
$\dot{m}$	mass flow rate (kg/s)
n	hours of operation/ runtime (h)
Nu	Nusselt number
P	pressure (kPa)
PR	pressure ratio
Pr	Prandtl number
$\dot{Q}$	heat transfer (kW)
Re	Reynolds number
s	specific entropy (kJ/(kg-K))
T	temperature (°C)
U	overall heat transfer coefficient (kW/m^2-K)
u	velocity of fluid (m/s)
v	specific volume (m^3/kg)
$\dot{W}$	power (kW)
x	concentration fraction (%)

Greek symbols

Δ	difference
ε	effectiveness
η	efficiency
μ	viscosity
ρ	density
σ	surface tension of fluid

Abbreviations

BEP	break-even point
CCH	combine cooling and heating
CCHP	combined cooling, heating and power
CCP	combine cooling and power
CHP	combined heat and power
CSB	coefficient of structural bond
CVCARS	cascaded vapor compression absorption refrigeration system
LMTD	logarithmic mean temperature difference
ORC	organic Rankine cycle
PG	propylene glycol
PTC	parabolic trough collector
SOFC	solid oxide fuel cell
SPP	simple payback period
USD	United States dollars
VARS	vapor absorption refrigeration system
VCRS	vapor compression refrigeration system

Subscript

0	ambient condition
a	absorber
c	condenser
cc	cascade condenser
comp	compressor
d	desorber
e	evaporator
ele	electric
ev	expansion valve
exp	expander
h	heater
HE	heat exchanger
i	internal/inside or state points
in	inlet
int	intermediate
IP&C	integration-piping and other component
k	period of repayment
l	liquid
o	external/outer
O&M	operation and maintenance
out	outlet
p	pump
prv	pressure reducing valve
s	isentropic
sa	stand-alone
shx	solution heat exchanger
sys	system
UE	unit electricity
v	vapor

cooling cycle and the calculated energetic and exergetic efficiencies are 88% and 28%, respectively. Ahmadi et al. [9] performed exergo-environmental analysis of gas turbine based ORC integrated absorption cooling system and reported 89% energy efficiency. Maraver et al. [10] analyzed biomass based trigeneration system and reported that the n−pentane, toluene, and siloxanes are better working fluids for high condensing temperatures (60 to 80 °C). Buonomano et al. [11] studied energy-economic aspects of geothermal and solar thermal energy powered ORC integrated absorption cooling system and reported 2.5–7.6 years of payback period. Chaiyat and Kiatsiriroat [12] focused on feasibilities of energy, economic and environment aspects of diesel burner powered ORC with absorption cooling system and reported 10 years of payback period. Karellas and Braimakis [13] analyzed micro-scale solar ORC integrated compression refrigeration cycle and reported 3% overall system efficiency and 7 years of payback period. Zare [14] performed thermodynamic optimization of ORC integrated absorption cooling cycle for trigeneration application and reported isobutene as a promising working fluid compared with *n*-pentane, R245fa, and R152a. Chang et al. [15] analyzed hybrid proton exchange membrane fuel cells (PEMFC) and solar energy based ORC with compression refrigeration system. Akrami et al. [16] carried out energetic and exergo-economic assessment of geothermal ORC integrated absorption cooling cycle and reported 35% energy efficiency and 49% exergy efficiency.

Cascaded vapor compression-absorption refrigeration system (CVCARS) maintains the advantages of both vapor compression and vapor absorption system while minimizing the limitations as well [18]. The electricity consumption in cascade refrigeration system is reduced by 61% and COP of compression section is improved by 155% compared with the conventional equivalent VCRS [18]. Recently, Patel