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Multi-objective optimization of a combined cooling, heating and power system driven by solar energy

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ABSTRACT

This paper presented a multi-objective optimization of a combined cooling, heating and power system (CCHP) driven by solar energy. The flat-plate solar collector was employed to collect the solar radiation and to transform it into thermal energy. The thermal storage unit was installed to storage the thermal energy collected by the collectors to ensure a continuous energy supplement when solar energy was weak or insufficient. The CCHP system combined an organic Rankine cycle with an ejector refrigeration cycle to yield electricity and cold capacity to users. In order to conduct the optimization, the mathematical model of the solar-powered CCHP system was established. Owing to the limitation of the single-objective optimization, the multi-objective optimization of the system was carried out. Four key parameters, namely turbine inlet temperature, turbine inlet pressure, condensation temperature and pinch temperature difference in vapor generator, were selected as the decision variables to examine the performance of the overall system. Two objective functions, namely the average useful output and the total heat transfer area, were selected to maximize the average useful output and to minimize the total heat transfer area under the given conditions. NSGA-II (Non-dominated Sort Genetic Algorithm-II) was employed to achieve the final solutions in the multi-objective optimization of the system operating in three modes, namely power mode, combined heat and power (CHP) mode, and combined cooling and power (CCP) mode. For the power mode, the optimum average useful output and total heat transfer area were 6.40 kW and 46.16 m^2. For the CCP mode, the optimum average useful output and total heat transfer area were 5.84 kW and 58.74 m^2. For the CHP mode, the optimum average useful output and total heat transfer area were 8.89 kW and 38.78 m^2. Results also indicated that the multi-objective optimization provided a more comprehensive solution set so that the optimum performance could be achieved according to different requirements for system.

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1. Introduction

Nowadays, energy consumption and carbon emission are becoming increasingly urgent issues. The multi-demand of energy for users has led to plenty efforts made by scientists to integrate multi-energy systems to achieve a higher efficiency. In this situation, the combined cooling, heating and power system (CCHP) has proved to be an efficient way to achieve energy saving and economic saving as well as to reduce the emission of pollutants [1,2]. Absorption chiller, compression refrigerator or ejector chiller can be used in the CCHP system to produce cooling capacity.

A large amount of works focused on CCHP systems have been carried out on the performance optimization considering the cost criterion. The linear programming model and the non-line programming model were employed to conduct the economic optimization of the CCHP system to obtain the minimum value of the cost of energy [3–5]. Ren et al. [6] developed a mixed integer nonlinear programming model to optimize the annual cost of a residential CCHP system. Tichi et al. [7] employed a particle swarm algorithm to minimize the cost function for different CHP and CCHP systems in an industrial dairy unit. It could be confirmed that the CCHP system was more efficient in energy saving.

Except for the economic index, the CCHP system performance can be additionally determined by thermodynamic and environmental criteria. Several articles also carried out additional analysis from the perspective of thermodynamics or environmental aspects. Chen et al. [8] conducted an exergoeconomic performance optimization of a CCHP system with a closed Brayton cycle. The fossil fuel energy savings and the CO_2 emissions were compared with the optimization results of a conventional system to evaluate the system performance more comprehensively. Oh and Seo et al. [9,10]

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Nomenclature

A	area, m^2
Bo	boiling number
C_p	specific heat at constant pressure, kJ/kg K
D	diameter, m
E	exergy, kW
F'	collector efficiency factor
F_R	heat removal factor
h	convection heat transfer coefficient, W/m^2 K; enthalpy, kJ/kg
I	hourly radiation, W/m^2
m	mass flow rate, kg/s
Nu	Nusselt number
P	pressure, MPa
Pr	Prandtl number
Q	heat rate, kW
R	tilt factor for radiation
Re	Reynolds number
S	incident solar flux, W/m^2
T	temperature, K; Time, h
U	loss coefficient, W/m^2 K; heat transfer coefficient, W/m^2 K
V	volume, m^3
W	pitch of tube, m; power, kW
x	vapor quality

Greek letters

α	absorptivity
β	Chevron angle of the plates
γ	ratio of the average useful output to the total heat transfer area
δ	thickness, cm
Δt_m	log mean temperature difference between hot side and cold side, K
η	efficiency, %
λ	thermal conductivity, W/m K
ρ	density, kg/m^3
τ	transmissivity; Time, h
ϕ	latitude, °

Subscripts

a	ambient; absorption
b	beam radiation
c	cold side
cond	condenser
cool	cooling
CND	condenser
d	diffuse radiation; daily
Eq	equivalent
EVP	evaporator
h	hot side; hydraulic diameter of flow channel
heat	heat
heater	heater
in	input
I	inlet; inner
l	loss; liquid phase
L	liquid in the water tank
FC	flat-plate collector
load	load
m	mean
max	maximum
min	minimum
net	net
out	output
o	outer
p	collector plate
pinch	pinch point
pump	pump
r	reflected radiation
s	isentropic point; Sun
solar	solar
t	tank
tot	total
turbine	turbine inlet
TBN	turbine
u	useful heat gain
v	vapor phase
VG	vapor generator
w	water in the tank
water1	water into the solar collector
water2	water into the vapor generator

used the mixed integer linear programming models to minimize the total annual cost of trigeneration systems in commercial and residential sectors. Arcur et al. [11] conducted the economic optimization of a trigeneration system in an energetically complex context by using a mixed linear programming model. Then, the energetics and environmental analysis were conducted based on results of the economic optimization to achieve a better system performance.

In order to evaluate the system performance comprehensively, certain researches focused on the optimization of CCHP systems were performed concerning simultaneously energetic, economic and environmental aspects. The single-objective optimizations for the CCHP system [12–15] were conducted by integrating primary energy consumption (PEC), operation cost (OC), and carbon dioxide emissions (CDE) or other index as the objective function respectively. The results demonstrated that there was not an optimal condition where each objective all reached the optimum value. Liu et al. [16] utilized the sequential quadratic programming (SQP) algorithm to solve the optimization problem of a CCHP system. The ratio of electric cooling to cool load was varied to minimize the objective function which was made up of three parts, namely the primary energy consumption, the hourly and annually total cost and the greenhouse gas (GHG) emission.

However, much work has been done on the single-objective optimization of the CCHP system, while few studies have been investigated in the multi-objective optimization. Abdollahi and Meratizaman [17–19] used the genetic algorithm to conduct the multi-objective optimization of a CCHP system. The objectives functions were selected from the view of thermodynamic, economic and environmental aspects. A two-stage optimal planning and design method was applied for a CCHP system [20]. Non-dominated Sorting Genetic Algorithm-II (NSGA-II) was employed in multi-objective optimization on the first stage, and the mixed-integer linear programming algorithm on the second stage.

All of these researches above have been devoted to CCHP powered by fossil fuels which will be limited with the growing crisis of energy shortage and are harm to environment with CO_x and NO_x emissions. The renewable energies, including hydraulic energy, hydrogen energy, solar energy and so on, were clean and inexhaustible, which would contribute to resolve the problem of

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