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A new combined cooling, heating and power system driven by solar energy

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ABSTRACT

A new combined cooling, heating and power (CCHP) system is proposed. This system is driven by solar energy, which is different from the current CCHP systems with gas turbine or engine as prime movers. This system combines *a* Rankine cycle and *an* ejector refrigeration cycle, which could produce cooling output, heating output and power output simultaneously. The effects of hour angle and the slope angle of the aperture plane for the solar collectors on the system performance are examined. *Parametric optimization* is conducted by means of genetic algorithm (GA) to *find* the maximum exergy efficiency. It is shown that the optimal slope angle of the aperture plane for the solar collectors is 60° *at 10 a.m. on June 12*, and the CCHP system can reach *its* optimal performance *with the slope angle of 45° for the aperture plane* at midday. It is also shown that the system can reach the maximum exergy efficiency of 60.33% under the conditions of the optimal slope angle and hour angle.

1. Introduction

The trigeneration concept refers to the possibility of efficiently and profitably combining cooling, heating and power production (CCHP) to satisfy the consumption needs during the energy system operation. In a competitive energy market framework, the adoption of CCHP systems may become profitable with respect to traditional systems, where electricity, heat, and cooling are produced or purchased separately.

There are several current CCHP technologies to perform the trigeneration according to the prime movers, such as steam turbine, reciprocating internal combustion engine, gas turbine, micro gas turbine, stirling engine, fuel cell. Wang et al. [1] had made an extensive and an intensive review of CCHP in the literature. Wang et al. [2,3] also investigated the CCHP system driven by stirling engine and gas turbine. Li et al. [4] conducted the energy utilization evaluation for the CCHP systems mainly with gas engine and gas turbine as prime movers.

Although steam turbine, reciprocating internal combustion engine and gas turbine that can be considered as the conventional prime movers still make up most of the gross capacity being installed, and micro gas turbine, Stirling engine and fuel cell present a promising future for prime movers in CCHP system, the current CCHP technologies must inevitably consume the fossil fuels, which would disappear with energy consumption and economic development in the future. So, it is necessary to utilize renewable energy.

The main objective of the present study is to propose a new combined cooling, heating and power (CCHP) system driven by solar energy. This system combines Rankine cycle and ejector refrigeration cycle, and produces cooling output, heating output and power output simultaneously. The ejector refrigeration cycle, which many studies [5–11] have been devoted to, is different from the absorption refrigeration cycle in most of CCHP systems. *It has some advantages such as fewer movable parts* and low operating, installation and maintenance cost. In addition, the ejector refrigeration cycle has the possibility of using a wide range of refrigerants with the system.

In the present study, the simulation of the CCHP system driven by solar energy is achieved using a simulation program. The effects of hour angle and the slope angle of the aperture plane for the solar collectors on the system performance are examined. In addition, the parameter optimization is achieved with exergy efficiency as the objective function by means of genetic algorithm under the given condition.

2. System description

The proposed CCHP system is driven by solar energy, and combines the Rankine cycle and the ejector refrigeration cycle, which could produce cooling, heating and power simultaneously. Fig. 1 illustrates the CCHP system. The overall system is divided into

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Nomenclature

A	surface area of solar collectors, m^2
b	width of absorber, m
c	heat capacity, $kJ\,kg^{-1}$
C	concentration ratio
D	diameter, m
E	exergy, kW
h	enthalpy, $kJ\,kg^{-1}$
H	height, m
I	hourly radiation, $W\,m^{-2}$
k	heat transferring coefficient, $W\,m^{-2}\,K^{-1}$
L	length of tube, m
m	mass flow rate, $kg\,s^{-1}$
ma	average number of reflections
n	the day of the year
N	number of tubes
p	pressure, MPa
Q	heat load, kW
R	tilt factor; ratio
s	entropy, $kJ\,kg^{-1}\,K^{-1}$
S	total effective flux, $W\,m^{-2}$
t	temperature, °C; time
T	temperature, K
u	velocity, $m\,s^{-1}$
U	overall loss coefficient, $W\,m^{-2}\,K^{-1}$
W	width, m

Greek letters

α	absorptivity of the absorber surface
β	slope angle of the aperture plane for solar collectors, °
δ	declination
η	efficiency
θ	angle of incidence
μ	entrainment ratio
ρ	reflectivity of the concentrator surface; density, $kg\,m^{-3}$
τ	transmissivity of the cover
ω	hour angle, °
φ	latitude, °

Subscripts

a	acceptance half angle
b	beam
br	branching
B	boiler
C	condenser
d	diffuse radiation; diffuser section of ejector
e	effective
exg	exergy
extr	extraction
E	evaporator
fi	inlet of solar collectors
fo	outlet of solar collectors
g	global
hc	average temperature of heater
H	heater
i	Inlet
inst	Instantaneous
l	uniform
lo	Loss
m	mixing section of ejector
mf	mixed fluid
n	nozzle
n1	inlet of nozzle
n2	outlet of nozzle
NET	Net
p	pressure
pf	primary flow
P1	pump 1
P2	pump 2
s	isentropic process
sc	average temperature of solar collectors
sf	secondary flow
thm	thermal
T	turbine
u	useful
z	zenith angle
0	environment

two subsystems: the solar collector subsystem and the CCHP subsystem.

2.1. The solar collector subsystem

This subsystem consists of solar collectors, a thermal storage tank and an auxiliary heater. The solar collectors are used as a main energy source to supply heat to the system. The thermal storage tank is used as the thermal *source* when solar radiation is not sufficient. The auxiliary heater is installed as the backup energy source to boosts the temperature of thermal storage tank to the allowable reference temperature when the temperature of thermal storage tank drops below the allowable reference temperature.

A compound parabolic collector (CPC) is used to collect the solar radiation because it achieves higher concentration for large acceptance angle and requires only intermittent sun-tracking. In addition, the CPC can achieve the higher temperature than flat plate collector for power generation. In the present study, the symmetric CPC with flat absorber is placed on a horizontal east–west axis and oriented with its aperture plane sloping at an angle of 45°.

The hourly global radiation I_g reaching a horizontal surface on the earth is given by:

$$I_g = I_b + I_d \tag{1}$$

where

$$I_b = I_{bn} \cos \theta_z \tag{2}$$

where I_{bn} is beam radiation in the direction of the rays, and θ_z is angle of incidence on a horizontal surface, i.e. the zenith angle.

It is postulated that for a clear cloudless day:

$$I_{bn} = A \exp\left[-\frac{B}{\cos\ \theta_z}\right] \tag{3}$$

and

$$I_d = C I_{bn} \tag{4}$$

where A, B and C are constants [12].

Since CPC for absorbing radiation is tilted at an angle to the horizontal, it is necessary to calculate the tilt factor for radiation.