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Thermo-economic analysis and multi-objective optimization of absorption cooling system driven by various solar collectors

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ABSTRACT

This research presents a combination of thermo-economic analysis and multi-objective optimization of a 10 kW single-effect ammonia-water solar absorption cooling system. A thermodynamic model is derived, and energy-exergy analyses are conducted. Also, the effects of various solar collector types including a flat plate, evacuated tube, compound parabolic, and parabolic trough collectors on the system performance are examined at different ambient temperatures. The thermodynamic analysis indicates that by increasing heat source temperature, the coefficient of performance and exergy efficiency of the system reach their highest values, while they occur in lower heat source temperature as the ambient temperature is decreased. The exergy efficiency is also found to decrease with the increment of evaporator, absorber, and condenser absorber temperatures. Furthermore, for determining the optimum operating conditions, a multi-objective optimization is performed by using an efficient particle swarm optimization technique with five objective functions. The corresponding results reveal that the solar absorption cooling system with evacuated tube collectors is the most economical solution with a total cost of 7.2 k€ and 24 m^2 collector area. It is found that the parabolic trough collector system has the highest solar exergy efficiency of 0.046, which occurs at the high ambient temperature and low evaporator temperature. This system also has higher solar performance coefficient up to 0.447 indicating its great efficiency.

1. Introduction

Energy consumption has significantly increased in the worldwide during the last few years due to increase of population, quality of life, and industrial activities [1]. By 2010, residential buildings consumed about 55% of the world annual energy for cooling [2], and it is forecasted that the worldwide power consumption for air conditioning would experience a 33-fold increase by 2100 [3]. Apart from the significant high-energy consumption of air conditioners, the chlorinated fluorocarbon compounds are used in conventional mechanical vapor compression systems; which lead to the depletion of the ozone layer when exposed to the atmosphere [4]. Thus, the need for the eco-friendly energy-saving cooling systems is felt now more than ever.

Recently, the absorption and adsorption/desiccant technologies have received significant attention as the alternative methods for cooling, instead of the conventional vapor compression cooling systems [5]. Furthermore, there is a sustainable energy source as solar radiation; which is clean, unlimited source, and available throughout the year in most of the developing nations. The integration of solar energy and cooling systems is able to decrease the electricity demand especially at the peak load hours [6]. Therefore, using the cooperative benefit of solar energy and absorption technology (which is market penetration among the sorption technologies [7]) could play an increasingly vital role in the future energy systems. Although the solar-driven absorption cooling systems (SACSs) are more expensive than the conventional cooling systems and have a lower coefficient of performance (COP), they are more attractive when electricity is expensive, unreliable, or unavailable [8]. The basic components of a SACS are comprised of solar energy collectors, heat storage reservoir, thermally driven cooling process, and heat rejection components to eliminate the waste heat of the cooling process [9]. Generally, solar energy collectors are divided into stationary and concentrating ones. The stationary solar collectors do not track the sun and include evacuated tube collectors (ETC), stationary compound parabolic collectors (CPC), and flat-plate

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Nomenclature

A	area (m^2)
C	specific cost (€/m^2)
c_p	heat capacity of water (kJ/kg °C)
C_R	concentration ratio
C_{system}	system cost (€)
D	diameter (m)
$\dot{E}_D$	exergy loss rate (kW)
e	specific exergy (kJ/kg)
h	specific enthalpy (kJ/kg)
I	solar radiation (W/m^2)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (kPa)
$\dot{Q}$	heat transfer rate (kW)
R	radiation factor
T	temperature (K or °C)
U_L	storage reservoir heat loss coefficient (W/m^2)
v	specific volume (m^3/kg)
V	volume (m^3)
$\dot{W}$	Work flow rate (kJ/s)
X	NH_3 mass concentration in mixture
F_R	heat removal factor

Greek letters

η	efficiency
δ	declination angle
ϕ	latitude angle
β	collector tilt angle
ρ	ground reflectance
$\tau\alpha$	transmittance-absorptance product

Acronyms

ACS	absorption cooling system
COP	coefficient of performance
CPC	compound parabolic collector
ETC	evacuated tube collector
FPC	flat plate collector
PTC	parabolic trough collectors
MLMOPSO	multi leader multi-objective particle swarm optimization
MINLP	mixed integer nonlinear programming
SACS	solar absorption cooling system
SCOP	solar coefficient of performance
SIF	social influence factor

Subscripts

abs	absorber
amb	ambient
b	direct
coll	collector
cond	condenser
d	diffuse
eva	evaporator
ex	exergy
gen	generator
hex	heat exchanger
p	pump
s	heat source
sr	Storage reservoir
sun	sun
T	total
u	useful
w	water

collectors (FPC) [10]. On the other hand, concentrating collectors track the sun and include parabolic trough collectors (PTC) [11].

Absorbent and refrigerant are the two materials that work together in an absorption cycle as a single solution. Many pairs have been proposed by researchers, but only H_2O-LiBr and NH_3-H_2O are commonly-used in refrigeration and air conditioning absorption systems [12]. The H_2O-LiBr absorption chillers are commonly used in residential scale applications and are difficult to be air cooled due to the crystallization problem which leads to narrower concentration, elevated absorber temperature (about 40 °C) and initial cost [13]. However, the solution of NH_3-H_2O has a low freezing temperature and the absorption chillers do not face the crystallization problem and can be used for a wider range of operational temperature and pressure [14].

Numerous researchers have examined the operating performance of SACSs using methodologies based on energetic, exergetic, economic, and environmental assessments. Said et al. [15] conducted an experimental study on the performance of an NH_3-H_2O SACS, and showed that the COP could be increased from 0.42 to 0.69, by changing the generator/condenser/evaporator temperatures from 145/45/−4 (°C) to 114/23/−2 (°C). Buonomano et al. [16] equipped a high-temperature solar cooling system with non-concentrating stationary solar thermal collectors, and revealed that their system overtook the reference PTC, especially by taking into account the impacts of defocusing and dust related to the of concentrating collectors tracking mechanisms in harsh environmental conditions. Shirazi et al. [17] examined the comparative performance of single-, double-, and triple-effects H_2O-LiBr absorption chillers through a systematic parametric study. ETCs were employed in couple with the single-effect chiller, while PTCs were used for double-, and triple-effect chillers. They showed that single-effect chiller requires more storage volume of about 70 L/m^2 compared to other chiller types with required storage volume of around 40–50 L/m^2. Their results also disclosed that when direct normal irradiance level is low, multi-effect chillers have no superiority over single-effect ones since they require larger collector area. In another study, Shirazi et al. [18] examined the operation of four different configurations of H_2O-LiBr SACSs with ETCs. A gas-fired heater was employed for backup in the first configuration. In the second configuration, a mechanical compression chiller was used providing additional cooling. The other configurations were similar to the second one, but using smaller chiller sizes, 50% and 20%. They reported that the second system provides the highest cooling efficiency offering about 72% solar fraction. Lubis et al. [19] investigated the performance of a single and double stage H_2O-LiBr absorption cooling system driven by combined gas and solar energy for Asian tropical climates. Using hot water (75–90 °C) and cooling water (28–34 °C), they observed that up to 60% energy saving can be achieved, with COP of 1.4–3.3. Khan et al. [20] examined the effectiveness of employing two alternative storage units (ice and chilled water) in a SACS. For chilling the water and cooling the space, the highest COP of 0.8 was achieved at generator/condenser/evaporator temperatures of 120/34.5/−2.2 °C. Bellos et al. [21] evaluated H_2O-LiCl and H_2O-LiBr working pairs in a SACS with single-effect chiller using FPCs. They analysed three different ambient temperatures and reported that LiCl-H_2O system outperforms H_2O-LiBr system in all environmental conditions and its optimal operating temperature is lower than that of H_2O-LiBr system. In another study, Bellos et al. [22] conducted a dynamic analysis on a SACS with single-effect H_2O-LiBr chiller coupled with ETCs made for the city of Athens, Greece. They varied the storage reservoir volume from 6 to 16 m^3 and the