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Research Paper

Exergetic, energetic and financial evaluation of a solar driven absorption cooling system with various collector types

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HIGHLIGHTS

- Four solar collectors (FPC, ETC, CPC, PTC) are tested in an absorption cooling system.
- The comparison criteria are the COP, the exergetic efficiency and the cost.
- The use of ETCs leads to lower investment cost and to lower land use.
- PTCs perform better energetically and exegetically but they have high cost.

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ABSTRACT

Solar energy utilization for cooling applications is analyzed in this study. A single effect absorption chiller operating with LiBr–H_2O is the cooling sorption machine which is coupled with a collector field. The cooling demand is 100 kW at 10 °C for Athens (Greece) in summer. Four different collector types are tested in order to predict the most suitable solution for this study case. More specifically, flat plate collectors, evacuated tube collectors, compound parabolic collectors and parabolic trough collectors are investigated under the same conditions. An exergetic optimization of every system gives the optimum solution of every case, which leads to minimum collecting area. A financial comparison between the four optimized systems proves that evacuated tube collectors are the most beneficial technology. On the other hand, system with parabolic trough collectors is the exergetic optimum one, but its high capital cost renders it an unprofitable solution. The analysis is made in steady state conditions with Engineer Equator Solver (EES), a very useful energy tool.

1. Introduction

The population growth and the new lifestyle lead to greater energy consumption worldwide. One of the most remarkable examples is the increase in air-conditioning demand because of the higher comfort standards in buildings [1–3]. Simultaneously, the fossil fuels depletion and the worldwide problem of greenhouse gas emissions create obstacles in covering the air-condoning demand. This situation renders the utilization of Renewable energy sources vital for our society. Solar energy is the most abundant, cheap and low CO_2 emissions renewable energy [4–6] leading the researchers to analyze new and innovative solar collectors and systems. Especially for countries with high radiation level, solar energy is a promising energy source for the future. Greece belongs to these countries, with a daily solar potential of about 4.35 kW h m^{-2} [7,8].

This situation makes solar cooling technologies very important for our society now and in the future. The most mature cooling technology driven by solar energy is sorption machines, absorption, adsorption and desiccant. The absorption chillers perform better than the other sorption machines giving greater COP, and for this reason have been evolved in the last years. Especially, the single effect absorption chiller with LiBr–H_2O is used worldwide, coupled with various solar systems [9–11]. In every case, the goal is the optimization and the development of the systems in order to be more efficient. The economic aspects of solar cooling systems should also be taken into account in order to determine the sustainability of every system [12,13]. Furthermore, exergetic analysis is needed in order to design by an optimum way with the higher possible exploitation of the energy source. The exergetic efficiency of the usual solar cooling systems is significant low, fact that makes obvious the great margin for improvements. Many

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Nomenclature

A_c	collecting area (m^2)
C_A	specific cost of collector (€ m^{-2})
C_R	concentration ratio
COP	coefficient of performance
C_V	specific cost of storage tank (€ m^{-3})
D	diameter (m)
E	exergy flow (kW)
G	solar radiation (W m^{-2})
h	specific enthalpy (kJ kg^{-1})
K_{system}	system cost (€)
L	length (m)
m	mass flow rate (kg s^{-1})
M	the one third of storage water mass (kg)
Q	heat rate (W)
R_{bm}	mean beam radiation factor
SCOP	solar coefficient of performance
T	temperature (K)
t	time (s)
U_L	tank total heat loss coefficient (W m^{-2} K)
V	tank volume (m^3)
w_p	pump specific work (kJ kg^{-1})
X	LiBr mass concentration in mixture

Greek symbols

β	collector slope (°)
η	efficiency
ξ	vapor quality
ρ	ground reflectance
ρ_w	water density (kg m^{-3})
Φ	latitude (°)

Subscripts and superscripts

A	absorber
am	ambient
b	beam
c	condenser
chill	chiller
col	collector
d	diffuse
E	evaporator
eff	effective
ex	exergy
Hex	heat exchanger
in	inlet
G	generator
loss	heat losses
max	maximum
opt	optimum
out	outlet
rec	receiver
S	heat source
solar	solar energy
*st*1	1st zone of the storage tank
*st*2	2nd zone of the storage tank
*st*3	3rd zone of the storage tank
Str	strong solution
sun	sun
T	titled
u	useful
w	weak solution

studies use this technique [14–16] in order to predict the most efficient solutions.

Balaras et al. [17] analyzed about 50 solar-powered cooling systems in European and Mediterranean countries and the final results shown primary energy savings of about 50%. Ghafoor [18] showed that the C.O.P. of absorption chillers lies between 0.6 and 0.8 for generator inlet temperature between 70 °C and 100 °C. They also marked that the ratio of collector field area to storage tank volume ranges from 8 to 100 (m^{-1}), something that are taken into consideration in this study. In other researches, various types of solar collectors for solar cooling applications have been analyzed, as flat plate collectors [19], evacuated tube collectors [20] and parabolic trough collectors [21]. The last one has been developed a lot the last years [22–24] because of their high efficiency in high temperature levels. In solar adsorption refrigeration cycles, evacuated tube collectors [25] and parabolic trough collectors [26] have been also analyzed and the final results showed lower COP than absorption systems.

In this work four different solar collector types are tested in the same cooling system in order to predict the most suitable collector type. The presented comparison is exergetic, energetic and financial by taking into account the way that the energy is exploited and the final capital cost of every investment. The absorption system is a single effect absorption chiller working with LiBr–H_2O, the most prevalent system. The analyzed collectors are the usual flat plat collectors (FPC), the efficiently evacuated tube collectors (ETC) and two concentrated collectors, compound parabolic collectors (CPC) and parabolic trough collectors (PTC). The data for the collector efficiency curves are adopted from other similar studies, which are mentioned in the next paragraph. The simulation tool is Engineering Equator Solver (EES) and the system is simulated in steady state. Many assumptions are made in this study, because the problem has many parameters. The main goal of this study is to determine the heat source temperature, the water temperature in the inlet of generator, which leads to lower solar collecting area for every collector type. The developed model is presented with many details in order the method to be clear and all the assumptions are validated by other studies in literature.

2. Theory and examined system

2.1. Solar collector performance

Solar energy is the energy source of the analyzed system. The solar energy potential of the solar field is able to be calculated from the collector aperture and the effective radiation on them. Eq. (1) shows the way that the available solar energy is determined.

$$Q_{solar} = A_c \cdot G_{eff}, \tag{1}$$

The effective radiation is different for every collector. FPC and ETC uses the beam and the diffuse radiation, while the PTC only the beam because it belongs in imaging concentrators with a specific image of the sun in the absorber. On the other hand, CPC with a lower concentration ratio ($C_R < 5$) [27] exploits beam radiation and a part of the diffuse. Concentration ratio determination is presented in Eq. (2) and the effective radiation of every collector in Eq. (3).

$$C_R = \frac{A_c}{A_{rec}}, \tag{2}$$

$$G_{eff} = \begin{cases} G_T, & \text{for FPC and ETC} \\ G_{cpc}, & \text{for CPC} \\ G_b, & \text{for PTC} \end{cases}, \tag{3}$$