Energy Conversion and Management 137 (2017) 34–48

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Energetic, exergetic and financial evaluation of a solar driven absorption chiller – A dynamic approach

Evangelos Bellos *, Christos Tzivanids, Christoforos Symeou, Kimon A. Antonopoulos

National Technical University of Athens, School of Mechanical Engineering, Thermal Department, Heroon Polytechniou 9 Zografou, 15780 Athens, Greece

ARTICLE INFO

Article history:
Received 12 October 2016
Received in revised form 8 January 2017
Accepted 14 January 2017

Keywords:
Solar cooling
ETC
Exergetic analysis
Financial analysis
Dynamic simulation

ABSTRACT

In this study, a solar cooling system of 100 kW is analyzed parametrically in dynamic basis for the city of Athens, Greece. The objective of this study is the design of a sustainable system, using energetic, exergetic and financial criteria. The examined system includes evacuated tube collectors, storage tank and a single stage absorption chiller operating with LiBr-H_2O working pair. Different combinations of collecting areas and storage tank volumes are tested in order to determine the most suitable cases exergetically. These optimum cases are evaluated financially and finally the system with the higher financial indexes is selected as the most suitable. More specifically, the collecting area is analyzed from 150 m^2 to 600 m^2 and the storage tank from 6 m^3 to 16 m^3. Finally, 450 m^2 of evacuated tube collectors with a 14 m^3 storage tank was proved to be the optimum solution financially with 15 years payback period and 67 k€ net present value.

1. Introduction

The role of renewable and sustainable energy sources in our society becomes more and more important because of the environmental threats, the fossil fuel depletion and the increasing price of electricity [1]. Solar energy is the most abundant and easily utilized energy source, especially for countries with high solar potential, as Greece [2]. Solar energy can be utilized in domestic water heating applications, for space heating, for space cooling with sorption machines, for industrial heat production and for electricity production with solar power plants and with photovoltaics collectors [3]. Among these applications, solar cooling seems to have the best compatibility between source supply and load demand [4]. Moreover, solar cooling technologies aid the decrease of high peaks of electricity consumption is summer which creates severe problems in the grid energy distribution [5].

Up today, solar cooling technologies are based on sorption machines, with absorption chillers to be the most mature technology. The most usual working pairs in the absorption chillers are lithium bromide-water (LiBr-H_2O) for temperature levels greater than 5 °C and water-ammonia (H_2O-NH_3) for producing cooling in extremely low temperature levels [6]. Alternative working pairs have been examined [7–9], as lithium chloride-water (LiCl-H_2O), lithium nitrate-ammonia ($LiNO_3$-NH_3), ammonia-calcium chloride (NH_3-$CaCl_2$) and ammonia/sodium thiocyanate (NH_3-NaSCN), with the first to be the most promising solution in the future [10]. According to the literature, LiBr-H_2O is the most usual working fluid for solar cooling applications, because of stability and efficiency reasons [11].

In the literature, many solar collectors' types have been tested in solar cooling applications; flat plate collectors (FPC), evacuated tube collectors (ETC), compound parabolic collectors (CPC) and parabolic trough collectors (PTC). The most usual absorption machines are single effects absorption machines, while there are systems with double or triple effect absorption chillers coupled with PTC or ETC [12–13]. The majority of these studies are focused on countries with high irradiation level as the Mediterranean countries and the Middle-East countries, while there are fewer studies for the Nordic countries [13-14].

Flat plate collectors have been analyzed in many studies with single effect absorption chillers. Tsoutsos et al. [15] examined this configuration for Crete (Greece) with TRNSYS and they concluded that 500 m^2 of FPC is able to lead to 70% solar coverage and to investment payback period of 12 years. Balghouthi et al. [16] proved that 30 m^2 of FPC with a storage tank of 800 l are able to cover the cooling load of a Tunisian building with a satisfying way. Angrisani et al. [17] compared FPC and ETC coupled with a single effect absorption chiller for the climate of southern Italy. They proved that ETC lead to higher yearly solar thermal efficiency and to higher solar fraction for the examined system. The use of ETC for producing cooling in Italy was also examined by Vasta

* Corresponding author.
E-mail address: bellose@central.ntua.gr (E. Bellos).

http://dx.doi.org/10.1016/j.enconman.2017.01.041
0196-8904/

Nomenclature

A	collecting area, m^2
A_{st}	storage tank outer area, m^2
CF	cash flow, €
COP_m	mean COP for the conventional refrigerator, –
COPs	solar coefficient of performance, –
c_p	specific heat capacity, J kg^{-1} K^{-1}
C_0	capital cost, €
d	diameter, m
D	daily energy, kWh
DD	number of the day in the year, –
E	exergy flow, kW
G_T	solar radiation, W m^{-2}
h	specific enthalpy, kJ kg^{-1}
H	daily total irradiation in the collector level, kWh m^{-2}
i	counter, –
j	counter, –
K_{ch}	chiller specific cost, € kW^{-1}
K_{el}	cost of electricity, € kWh^{-1}
K_{ETC}	specific cost of the ETC, € m^{-2}
$K_{O\&M}$	cost of operation and maintenance, %
K_{ref}	cost of refrigeration, € kWh^{-1}
K_{tank}	specific cost of the storage tank, € m^{-3}
L	length, m
m	mass flow rate, kg s^{-1}
M	project life, years
M_{st}	water mass in storage tank, kg
N	storage tank zones
N_D	day duration, hours
Q	heat rate, W
r	discount factor, %
t	time, s
t_{max}	time for the maximum ambient temperature, s
T	temperature, °C
T_{SUN}	sun temperature, K
UA	heat transfer coefficient, W K^{-1}
U_T	tank total heat loss coefficient, W m^{-2} K^{-1}
V	tank volume, m^3
W_p	pump power, W
X	LiBr mass concentration in mixture, %
Y	yearly refrigeration production, kWh
Z	daily exergy, kWh

Greek symbols

δ	solar declination, °
Δt	time step, s
η	efficiency
ρ	water density, kg m^{-3}
Φ	latitude, °

Subscripts and superscripts

A	absorber
am	ambient
C	condenser
ch	chiller
col	collector
D	daily
E	evaporator
ex	exergy
h	hot
HEX	heat exchanger
in	inlet
G	generator
loss	heat losses
m	mean
max	maximum
min	minimum
net	net gain
opt	optimum
out	outlet
r	refrigerant
ref	refrigeration
s	solar
st	storage tank
str	strong solution
sys	system
th	thermal
u	useful
w	weak solution

Abbreviations

COP	coefficient of performance
CPC	compound parabolic collector
ETC	evacuated tube collector
FPC	flat plate collector
IRR	internal rate of return
NPV	net present values
PP	payback period
PTC	parabolic trough collector
SCOP	seasonal coefficient of performance
SPP	simple payback period

et al. [18] and they concluded that the financial support policy is vital for these investments; something that is also has been stated by Angrisani et al. [17].

Al-Alili et al. [19] examined a solar powered absorption chiller with ETC for Abu Dhabi and they proved that the electricity consumption can be reduced to the half, compared to the conventional cooling systems. They stated that the falling cost of the solar equipment and the increasing rate of electricity are the key factors for the financial viability of solar cooling systems. Muye et al. [20] studied a solar absorption power-cooling system with ETC for Spain, while in India. They proved that this system produces greater amounts of cooling in the Spain, while India solar potential is higher. The reason for this interesting result is the higher ambient temperature in India which has a negative impact on the coefficient of performance (COP) of the chiller. Buonomano et al. [21] analyzed the use of a new ETC by TVP Solar in a solar cooling system with double stage absorption chiller. They also compared this configuration with the respective with PTC. According to the final results, ETC is the best solution because higher solar fraction can be achieved, because there are high optical losses in the case of PTC.

As it has been stated, the use of PTC can lead to satisfying results with double effect absorption chillers. These systems have been analyzed in the climate of Italy [22], Tunisia [23] and Greece [24]. A recent study [25] which compared FPC, ETC, CPC and PTC energetically and financially proved that ETC is the best solution because this technology utilizes also the diffuse solar energy.

According to the previous studies and their results, ETC is the most appropriate solar device for coupling with single effect absorption chillers. In majority of the studies, the systems are compared energetically and financially. In recent years, the exergetic analysis of absorption chillers [26–28] and of solar cooling systems [29,30] becomes more and more attractive, because this analysis