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Optimum design of a solar ejector refrigeration system for various operating scenarios

Evangelos Bellos*, Christos Tzivanidis

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

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ABSTRACT

The objective of this work is to examine a solar ejector refrigeration system under various operating scenarios. Evacuated tube collectors of 100 m^2 collecting area coupled to a storage tank of 4 m^3 are selected for feeding the generator of the refrigerator. The system is examined for different evaporator temperatures from −10 °C to 10 °C and for different heat rejection temperatures from 30 °C to 50 °C. In every case, the system is optimized by selecting the optimum ejector design and the optimum generator temperature. Different refrigerants are examined as R123, R245fa, R600a and R134a, while the emphasis is given to the R141b. The innovation of this work is based on the systematic examination and optimization of a great range of operating scenarios giving a clear image for the system performance. According to the final results, the R141b is found to be the best candidate in all the operating scenarios. More specifically, the maximum system COP is found to be 0.234 when the system produces refrigeration at 10 °C and rejects heat to the environment at 30 °C. The optimum generator temperatures are found to be from 114 °C to 157 °C and the cooling capacity is ranged from 1.85 kW up to 23.39 kW. The analysis is performed with a developed model in EES (Engineering Equation Solver) under steady-state conditions.

1. Introduction

Solar energy exploitation is one of the most promising ways for facing the numerous threads as the climate change, the increasing energy demand and the high electricity price [1–3]. Solar energy is able to be converted either to thermal energy with a solar thermal collector or directly to electricity with photovoltaic cells, the fact that makes it a flexible energy source [4,5]. Moreover, the high solar energy potential in a great variety of courtiers makes it a crucial renewable energy source for the present and the future.

The utilization of solar energy in refrigeration or cooling applications gains more and more attention the last years because of the high compatibility between the solar energy supply and the demand, especially in the cooling applications [6,7]. Furthermore, solar refrigeration/cooling is a technique which aids the reduction of electricity demands from the grid during the summer period [8,9]. The most usual solar refrigeration systems include sorption machines as absorption chillers, adsorption chillers or desiccant wheels. On the other hand, systems with ejectors are competitive to the previous technologies because of their lower cost and their lower complexity [10,11]. However, the ejector refrigerator has usually lower performance compared to sorption machines and thus a lot of research is conducted in order their design to be optimized [12].

There are numerous studies in the literature which examines and evaluates solar ejector refrigeration systems. Table 1 summarizes the most important literature studies about these systems. Totally there are 33 studies in the literature [13–45] and it is obvious that the most usual solar thermal collectors in these studies are the flat plate collectors (FPC) [13–26] and the evacuated tube collectors (ETC) [26–40], while there are only 5 studies about concentrating technologies [41–45]. Moreover, it is obvious that the most recent studies investigate systems with ETCs and these systems are generally more efficient than the respective with FPC. More specifically, the study of Huang et al. [26] proved the system COP can reach up to 0.19 with FPC and up to 0.28 with ETC.

Many studies in the literature have examined systems with booster compressor and/or with an auxiliary heater (usually boiler) in order to achieve constant heat supply to the generator. The studies with these modifications are highlighted in table 1, in the comment column. The studies without extra comment investigate systems driven by solar energy without other energy input.

The most usual refrigerants according to table 1 are the following: R134a, R141b, R114, R600a and R123, while the water is used in a great percentage of the studies. However, the utilization of water is

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

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Nomenclature

A_{col}	collecting area, m^2
A_T	storage tank outer area, m^2
c_p	specific heat capacity, kJ/kg K
E	exergy flow, kW
G_T	solar radiation, W/m^2
h	specific enthalpy, kJ/kg
m	mass flow rate, kg/s
P	pressure, kPa
Q	heat rate, kW
T	temperature, °C
T_{sun}	sun temperature, K
U_T	tank total heat loss coefficient, kW/m^2 K
$(UA)_g$	total heat transfer coefficient in the generator, kW/K
V	velocity, m/s
V_T	storage tank volume, m^3
W	work, kW

Greek symbols

ΔP	pressure drop, kPa
η	efficiency, –
μ	entertainment ratio, –
ρ	density, kg/m^3

Subscripts and superscripts

am	ambient
c	condenser
ch	chiller
col	collector
crit	critical
d	diffuser
e	evaporator of mechanical compression refrigerator
ex	exergy
in	inlet
is	isentropic
g	generator
loss	heat losses
low	low pressure in the mixing region
m	mixing region
max	maximum
mf	mixing flow
mn	motive nozzle
n	nozzle
o	reference
out	outlet
pf	primary flow
pu	pump
s	heat source to the generator
sf	secondary flow
sn	suction nozzle
sol	solar
st	storage tank
sun	sun
sys	system
st,1	storage tank first mixing zone
st,2	storage tank second mixing zone
st,3	storage tank third mixing zone
u	useful

Abbreviations

COP	coefficient of performance
CPC	compound parabolic collector
EES	engineering equation solver
ETC	evacuated tube collector
FPC	flat plate collector
GWP	global warming potential
ODP	ozone depletion potential
PTC	parabolic trough collector

restricted only to cooling applications because the minimum evaporator temperature has to be close to 5°C. Thus, the other refrigerants are suitable for cooling capacity in lower temperature levels.

In the literature studies for solar cooling systems with FPC, the impact of generator temperature on the system performance has been extensively examined. Sokolov et al. [14,15] examined solar refrigeration systems with R114 as the refrigerant. They found the optimum generator temperature close to 110 °C in the system without booster [14] and lower optimum values up to 100 °C for the system with booster compressor [15]. Huang et al. [17] found that the optimum generator temperature is lower for higher evaporator temperatures. More specifically the proved that for evaporating temperature equal to 8 °C and to −6 °C, the optimum generator temperatures are 95 °C and 105 °C respectively. Arbel and Sokolov [19] examined a system with booster and found optimum performance for generator temperatures in the range of 100–105 °C. Yapici et al. [24] found the optimum generator temperature equal to 74 °C for evaporator temperature equal to 10 °C.

In a comparative study, Huang et al. [26] found that the use of higher quality solar collector leads to higher performance. This result is explained by the higher optimum generator temperature in the systems with ETC or with improved FPC. These results indicate the need of using a special collector design for driving the ejector refrigeration systems. Among the studies with ETCs, the generator temperature optimization is a critical issue that has been highlighted. Guo and Shen [31] found the optimum generator temperature close to 85 °C for a system with an auxiliary heater. Varga et al. [32] found the optimum generator temperature for different configuration of the ejector. Chesi et al. [37] examined the yearly performance of a solar refrigeration system which can operate in two modes. The first mode is the conventional mechanical compression system, while the second is the ejector refrigeration system. After a simple sensitivity analysis, they found the optimum generator temperature close to 65 °C.

The last part of the literature studies investigates systems with concentrating technologies and ejector refrigeration system. The use of compound parabolic collectors (CPC) has examined only by Joemann et al. [41]. On the other hand, more attention has been given to the parabolic trough collectors (PTC) where there are four literature studies [42–45]. More specifically, Pollerberg et al. [43–45] have performed three important studies for the experimental evaluation of a system with PTC and ejector refrigeration system without auxiliary heater or booster. In their studies, they found the system COP to be close to 0.20, a relatively high value compared to the respective studies of Table 1 with only solar energy as the heat source. The main reason for this result is the high thermal efficiency of the PTCs. However, the use of concentrating technologies in solar refrigeration systems with ejectors has not been evolved because of the complexity of these solar collectors which is associated with the need of continuous tracking system.

The previous literature review gives a clear image of the existing situation in the literature about the solar ejector refrigeration systems. It is obvious that the use of ETCs is the most appropriate solar technology because of their relatively high efficiency and their simplicity in