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Energetic and exergetic investigation of a novel solar assisted mechanical compression refrigeration system

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ABSTRACT

The objective of this study is to present and to examine a novel solar assisted mechanical compression refrigeration system. Evacuated tube collectors are used in order to partially thermally compress the refrigerant, after the mechanical compressor. This design aims to reduce the electricity consumption using a renewable energy source, creating a sustainable system. The suggested design is analyzed parametrically in order to investigate its energetic and exergetic behaviour in various operating conditions and it is examined with EES (Engineering Equator Solver) in steady state conditions. The temperature levels in the evaporator and in the condenser, as well as the thermal compression fraction (expressed with the pressure ratio parameter), are the examined parameters. The final results proved that the optimum values of the pressure after the mechanical compressor is the 75% of the maximum pressure and for this case, energy savings from 15% to 25% can be achieved. Moreover, the specific collecting area is found to be relatively low, close to 2 m^2/kW for the optimum cases. The final results proved that the new design leads to energy savings in all the examined cases and especially in cases with higher evaporating temperature levels, a fact that makes it ideal for space cooling applications.

1. Introduction

Our society faces many problems associated with the energy production and management. Global warming, fossil fuel depletion and the increasing cost of the electricity are the main reasons which make the turn to renewable and sustainable solutions to be a mandatory issue [1–3]. Solar energy is one of the most promising technologies for producing heat and electricity for a great range of applications [4]. Air conditioning is one of the most energy-consuming technologies, especially for countries with hot climate [5–6].

Mechanical compression refrigerators are the conventional devices which produce the demanded cooling load by consuming electrical energy [7]. These devices operate with a coefficient of performance close to 3 [8–9], something that is depended on the operating conditions. Thus, a lot of research has been focused on finding alternative technologies for cooling production. The most usual idea is based on using heating instead of electricity for producing the demanded cooling load with a great variety of thermal machines. This heat is preferred to be taken from renewable energy sources as solar energy and geothermal energy, while the use of waste heat is an alternative and environmentally friendly idea [10–11]. The most usual techniques for using solar energy for refrigeration are absorption chillers, adsorption chillers, ejectors, desiccant wheels and hybrid systems.

Absorption chillers are machines which utilize thermal energy to produce cooling in a great range of temperature levels. For space cooling applications, the LiBr-H_2O working pair is usually used, while for lower evaporating temperatures, H_2O-NH_3 is the most preferable choice [12]. These chillers are varied from single and to multi-stage machines, with the first to operate with heat source temperature levels close to 100 °C, while the other to need higher driving temperatures, from 150 to 200 °C [13]. The single effect machines present COP close to 0.8, while double effect 1.4 and triple effect 1.8 [14]. Generally, various collector types have been proposed in solar cooling systems, as flat plate collectors (FPC), evacuated tube collectors (ETC), compound parabolic collectors (CPC) and parabolic trough collectors (PTC). In a recent study, Bellos et al. [15] proved that ETC is the most suitable technology financially for a solar cooling system with single stage absorption chiller. Shirazi et al. [14] performed a detailed comparison among single, double and triple effect solar cooling systems with absorption technology. Finally it was proved that ETC with single stage

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Nomenclature

a	pressure ratio, –
A_c	collecting area, m^2
A_{st}	storage tank outer area, m^2
COP_{el}	electrical coefficient of performance, –
c_p	specific heat capacity, kJ/kg K
d	diameter, m
E	exergy flow, kW
G_T	solar radiation, kW/m^2
h	specific enthalpy, kJ/kg
L	length, m
m	mass flow rate, kg/s
M	water mass in storage tank, kg
p	pressure, kPa
P	power, kW
Q	heat rate, kW
T	temperature, °C
T_{SUN}	sun temperature, K
T_0	reference temperature, K
(UA)	overall heat transfer coefficient in the vessel heat exchanger, kW/K
U_T	tank total heat loss coefficient, kW/m^2 K
v	specific volume of the refrigerant, m^3/kg
V	tank volume, m^3

Greek symbols

ΔT_{lm}	mean logarithmic temperature difference, K
η	efficiency, –
η_m	motor efficiency of the compressor, –
ρ	water density, kg/m^3

Subscripts and superscripts

am	ambient
aux	auxiliary
c	condenser
ch	chiller
col	collector
e	evaporator
el	electrical
ex	exergetic
h	high
heat	hear input in the vessel
hex	heat exchanger
in	inlet
is	isentropic
l	low
loss	heat losses
m	intermediate
opt	optimum
out	outlet
r	refrigerant
s	heat source
sol	solar
st	storage tank
sys	system
th	thermal collector
u	useful

Abbreviations

COP	coefficient of performance
CPC	compound parabolic collector
EES	engineering equation solver
ETC	evacuated tube collector
FPC	flat plate collector
PTC	parabolic trough collector

absorption chiller is a financially feasible solution with the demanded specific area from 2.5 to 5 $m^2/kW_{cooling}$.

Adsorption technology is a cooling technology which presents lower COP than absorption technology but the demanded driven temperature level is also lower. Usually, temperatures close to 80 °C are used with COP to be under 0.6 [12]. The most usual working pairs in adsorption cycles are the following [16]: activated carbon/ammonia, zeolite/water, silica gel/water and activated carbon/methanol. Many theoretical and experimental studies have been performed in solar driven adsorption systems. Zhai and Wang [17] investigated a solar driven adsorption system with ETC. The final results showed that the demanded specific collecting area was 8.82 m^2/kW, a high value due to the low COP which was ranged from 0.32 to 0.36. The driven temperature levels were ranged from 55 °C to 85 °C, low-temperature values which explain FPC utilization. Fasfous et al. [18] examined a system with FPC and adsorption chiller with a cooling load of 8 kW and specific collecting area equal to 5.81 $m^2/kW_{cooling}$. Luo et al. [19] investigated a similar system with specific collecting area 9.96 m^2/kW and mean COP close to 0.32. The low COP values lead to larger solar fields, as it was proved from the previous references.

Desiccant wheel systems are usually applied in space cooling applications. These configurations are open cycle systems which operate with air as working fluid for cooling and dehumidification systems. Li et al. [20] examined a desiccant solar cooling system with air collectors. The system COP was found close to 0.45 and the specific collecting area 3 m^2/kW.

Ejector cooling is a thermally driven system which can operate with low-temperature heat sources, as solar energy. The system simplicity and the lack of moving parts make it a reliable solution which antagonizes the mechanical compression refrigerators. Vidal et al. [21] examined and optimized a solar driven ejector system with FPC. The final results showed that the COP was 0.3, the specific collecting area 7.62 m^2/kW, the ratio of the collecting area to the storage tank 20 m^2/m^3 and the solar energy fraction was the 42% of the total demanded energy input.

Moreover, there are hybrid and alternative systems which combine different technologies together. Vidal and Colle [22] examined a solar assisted ejector-evaporator compression cycle, with R134a in the compression cycle and R141b for the thermally driven ejector cycle. The final results proved enhancement with COP reaching the value of 0.89. Meng et al. [23] investigated absorption-compression hybrid refrigeration cycle and the final results proved electricity savings up to 50%. Mira-Hernández et al. [24] examined a hybrid adsorption-mechanical compression refrigeration system with a liquid storage tank. This system was driven by photovoltaic panels with the overall COP close to 0.65 and the specific collecting area was close to 3 m^2/kW.

As it is obvious, numerous configurations have been proposed and examined for creating sustainable and low electricity consumption systems. In this study, a novel solar-assisted system is suggested and examined parametrically under thermodynamic basis. More specifically, in the present refrigeration cycle, the compression of the refrigerant is separated into two parts; the first is integrated with the compressor thus consuming grid electricity