Energy 72 (2014) 680–690

Contents lists available at ScienceDirect

Energy

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

Thermo-economic and environmental optimization of solar assisted heat pump by using multi-objective particle swam algorithm

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ARTICLE INFO

Article history:
Received 8 February 2014
Received in revised form
23 May 2014
Accepted 25 May 2014
Available online 20 June 2014

Keywords:
Solar assisted heat pump
Refrigerant
Total annual cost
Multi-objective particle swarm optimization

ABSTRACT

In this paper, a solar assisted heat pump is modelled and optimized. Solar panel surface areas, evaporator pressure, condenser pressure, capacity of heat storage tank as well as the value of superheating/sub-cooling in evaporator/condenser are selected as design parameters. MOPSO (Multi-objective Particle Swarm Optimization) algorithm is used to find the optimum value of design parameters where TAC (total annual cost) and COP (coefficient of performance) taken as two objective functions. TAC is included with sum of investment, operation and environmental costs. The optimization is separately performed for five working fluids including R123, R134a, R245fa, R407C and R22. The optimization results showed that the best studied working fluid is R245fa in both thermo-economical and environmental view point with 1746.1 $/year as TAC, 3.76 for COP and annual environmental cost of 81.825. The optimum results of R245fa as working fluid, showed 15.22%, 21.28%, 22.31% and 44.66% improvement in TAC compared with R134a, R123, R22 and R407C, respectively. Furthermore, COP improvement for R245fa was obtained 26.77%, 30.92%, 34.31% and 48.12% compared with R134a, R123, R22 and R407C, respectively.

1. Introduction

Energy is a crucial item in our daily life for almost everything including its production and usage directly affecting the environment. As a result of the decreased fossil fuel resources the solar can be appropriate alternatives which can be generated by solar panels. Due to the fact that this energy is abundant, renewable and clean without producing greenhouse gases, numerous researches have been carried out to use it in recent years.

Many experimental and theoretical studies concerning the modelling of DX-SAHPs (direct expansion solar assisted heat pumps) have been carried out in recent years. Omojaro and Breitkopf reviewed the DX-SAHP [1]. Also, large numbers of refrigerants with good usage potentials in DX-SAHP showed to exist. Chaturvedi et al. carried out the thermodynamic analysis of a two-stage DX-SAHP for high temperature applications and compared it with a single-stage DX-SAHP [2]. Kong et al. presented a modelling and system simulation of the designed DX-SAHP system for thermal performance analysis [3]. The refrigerant R22 considered as working fluid in the system. Mohanraj et al. applied the ANN (artificial neural network) to predict the performance of a DX-SAHP [4]. The performance parameters such as power consumption, heating capacity, energy performance ratio and compressor discharge temperature of a DX-SAHP based on solar intensities and ambient temperatures used to train the network. Kuang and Wang designed and experimentally investigated a multi-functional direct expansion solar assisted heat pump (DX-SAHP) system for domestic use [5]. The system employed a bare flat-plate collector array, a variable speed compressor, a storage tank and radiant floor heating unit. Xu Guoying et al. performed a simulation study on the operating performance of a solar–air source heat pump water heater [6]. In their work, a specially designed flat-plate heat collector/evaporator with spiral-finned tubes was used to obtain energy from both solar irradiation and ambient air for hot water heating. Huang Hulin et al. theoretically carried out the thermal performance of two different schemes of solar assisted heat-pump systems [7]. In first scheme, the evaporator of the heat pump was taken directly as the solar collecting plate and in the second scheme, the solar radiation was collected and stored as sensible heat in the fresh water solar pond with high efficiency. Hikmet Esen et al. used the artificial neural networks (ANNs) to predict performance of a horizontal ground coupled heat pump system [8]. The air temperature entering condenser unit, air temperature leaving condenser unit

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http://dx.doi.org/10.1016/j.energy.2014.05.095

Nomenclature

A	heat transfer surface area (m^2)
C	investment cost ($)
C_v	expansion valve coefficient
COP	coefficient of performance (–)
G	total solar energy incident on the collector (W/m^2)
h	enthalpy (kJ/kg K)
$\dot{H}$	rate of heat (kW)
$\dot{H}_h$	solar received radiation (kW/m^2)
$\dot{H}_t$	solar received radiation on slop surface (kW/m^2)
$\dot{G}_{oh}$	extra terrestrial solar radiation (kW/m^2)
i	interest rate (–)
I_{rad}	intensity of solar radiation (W/m^2)
k_T	cloud less index (–)
LHV	fuel lower heating value (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
n_{col}	number of solar panel (–)
N	number of month in a year (–)
p	pressure (kPa)
r_p	compressor pressure ratio (–)
TAC	total annual cost ($/year)
T	temperature (°C)
U	overall heat transfer coefficient (W/m^2 K)
$\dot{W}$	power (kW)
y	depreciation time (year)

Greek abbreviation

β	annual cost coefficient (–)
ψ_{em}	pollutant emission cost ($/kg)
ψ_{fuel}	fuel cost ($/kg)
Δp	pressure drop (kPa)
ψ_{el}	electricity unit cost ($/kWh)
τ	step size of variation in loads during a year (month)
ρ	density (kg/m^3)
η	efficiency (–)
β	panel surface angle (degree)
λ	latitude (degree)
α	electric cooling ratio (–)
δ	declination angle (degree)
ω	hour angle (degree)
$\dot{G}_{sc}$	solar constant (kW/m^2)

Subscript

a	actual
amb	ambient
b	auxiliary boiler
comp	compressor
cond	condenser
col	solar thermal collector
evap	evaporator
env	environment
i	inlet
inv	investment
LMTD	logarithmic mean temperature difference
o	outlet
op	operational
r	refrigerant
s	isentropic
stor	stored heat/storage tank
v	expansion valve

and ground temperatures were considered as input layer and the COPS (coefficient of performance of system) was in output layer for training the network.

Some researchers performed the solar assisted heat pump analysis with different environment-friendly refrigerants. The possibility of implementing the chosen natural working fluid in solar-boosted heat pumps performed by Chaichana et al. for domestic water heating applications [9]. R-744, R-717, R-290 and R-1270 considered as working fluids and compared with R22 in terms of their characteristics and thermo-physical properties, and thermal performance. Gorozabel Chata et al. analysed the thermal performance of a DX-SAHP with some refrigerants such as R-134a, R12, R22, R-404A, R-410A and R-407C [10]. Their results showed R-12 produced the highest value of COP, followed by R22 and R-134A. Mohanraj et al. performed the exergy assessment of a direct expansion solar assisted heat pump working with R22 and R407C/LPG mixture [11]. Also, the exergy destruction and exergy efficiency of each component of heat pump and of the whole system working with R22 and RM30 determined at different solar intensities and ambient temperatures. Mohanraj et al. reviewed the various experimental and theoretical studies performed around the globe with environment friendly alternatives such as hydrocarbons (HC), hydroflurocarbons (HFC) and their mixtures in refrigeration, air conditioning and heat pump applications [12]. Mohanraj et al. experimentally investigated a DX-SAHP working with R22 and mixture of R407C–liquefied petroleum gas (LPG) [13]. The results showed that R407C–LPG was an ozone friendly alternative option to phase out R22 in solar assisted heat pump applications.

Some researcher conducted the energy and exergy analysis of solar and ground source heat pump systems [14–18]. Many research works performed in the theoretical and experimental performance of a photovoltaic solar assisted heat pump [19–22]. An assessment was performed by Martin Kegel et al. on two solar assisted heat pump systems, where solar energy was coupled to the evaporator side to improve system performance during the heating season [23]. Chow et al. investigated the application potential of solar assisted heat pump system for indoor swimming pool space and water heating under the subtropical climatic condition of Hong Kong [24]. The results showed that the designed system could well satisfy the system energy demands. In addition, the performance of underground thermal storage in a solar-ground coupled heat pump systems for residential building was experimentally analysed by Wang and Qi [25]. A long-term reliability test of an integral-type solar assisted heat pump water heater was carried out by Huang and Lee [26].

In this paper after thermo-economic modelling of solar assisted heat pump (SAHP), this equipment is optimized by minimizing the total annual cost (TAC) and maximizing the total cycle COP. Solar panel surface area, evaporator pressure, condenser pressure, capacity of heat storage tank and the value of superheating/subcooling in evaporator/condenser are selected as six design parameters and Multi-objective Particle Swarm Optimization (MOPSO) algorithm is applied to provide the optimum solutions. As a summary, the followings are the contribution and novelty of this paper into the subject:

- Thermal modelling of heat pump assisted by solar panels.
- Applying four simultaneous system analysis including energy, performance, economic and environmental for equipment selection which is not considered by the previous works.