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Direct expansion solar assisted heat pumps – A clean steady state approach for overall performance analysis

Luca A. Tagliafico, Federico Scarpa*, Federico Valsuani

University of Genoa – DIME/TEC – Division of Thermal Energy and Environmental Conditioning, Via All'Opera Pia 15 A, 16145 Genoa, Italy

HIGHLIGHTS

- A new approach for the steady state analysis of solar assisted heat pumps is presented.
- The model is based on the inverse Carnot cycle and does not use fluid properties.
- The approach leads to an analytical steady state description of the system.
- The model effectively describes the averaged behavior of the considered system.
- The model appears suitable to be applied to embedded control systems.

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ABSTRACT

Traditional thermal solar panel technologies have limited efficiency and the required economic investments make them noncompetitive in the space heating market. The greatest limit to the diffusion of thermal solar systems is the characteristic temperatures they can reach: the strong connection between the user temperature and the collector temperature makes it possible to achieve high thermal (collector) efficiency only at low, often useless, user temperatures.

By using solar collectors as thermal exchange units (evaporators) in a heat pump system (direct expansion solar assisted heat pump, DX-SAHP), the overall efficiency greatly increases with a significative cut of the associated investment in terms of pay-back time.

In this study, an approach is proposed to the steady state analysis of DX-SAHP, which is based on the simplified inverse Carnot cycle and on the second law efficiency concept. This method, without the need of calculating the refrigerant fluid properties and the detailed processes occurring in the refrigeration device, allows us to link the main features of the plant to its relevant interactions with the surroundings. The very nature of the proposed method makes the relationship explicit and meaningful among all the involved variables.

The paper, after the description of the method, presents an explanatory application of this technique by reviewing various aspects of the performance of a typical DX-SAHP in which the savings on primary energy consumption is regarded as the main feature of the plant and highlighted in a monthly averaged analysis.

Results agree to those coming from a common standard steady state thermodynamic analysis. The application to a typical DX-SAHP system demonstrates that a mean saved primary energy of about 50% with respect to standard gas burner can be achieved for the same user needs. Such a result is almost independent from the type of flat plate solar panel used (double or single glazed, or even bare panels) as a result of using an optimal collector working temperature.

1. Introduction

Solar energy is acknowledged to be the most effective form of renewable energy in the field of civil plants and in those applications in which the thermal or electrical power required is compatible with spatial and economic constraints.

* Corresponding author. Fax: +39 (0)10311870.
E-mail address: fscarpa@ditec.unige.it (F. Scarpa).

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Nomenclature

Symbols & acronyms

A	heat transfer surf. area (panel/evap.), m^2
COP	coeff. of performance
E	energy, J
G	solar irradiation, W m^{-2}
M	water mass, kg
Mc	thermal capacity, J K^{-1}
Pc	compressor power, W
PES	primary energy savings
q	heat transfer rate, W
Q	heat energy transfer, J
R	thermal resistance, K W^{-1}
T	temperature, K
U	global heat transfer coeff., W m^{-2} K^{-1}
VCC	variable capacity compressor
W	energy transfer by work, J

Subscripts

aux	auxiliary
b	burner
c	compressor
cd	of the condensing fluid
DX	direct expansion (SAHP)
e	of the ambient (environmental)
ev	of the evaporating fluid
el	electric
f	fluid
G	relative to solar irradiation
hp	heat pump mode
id	ideal
II	second law of thermodynamics
in	into the evaporator, into the fluid
m	monthly averaged
out	out of the condenser
p	solar panel
pr	primary (energy)
stg	storage tank, reservoir
T	traditional (solar panel)
tap	tap water
u	user

Greek symbols

α	absorbance
χ	saved primary energy index
Δt	time interval, s
ε	specific electric energy consumption
η	efficiency
τ	transmittance

Owing to the variability of solar radiation and the low conversion efficiency of such plants, thermal and photovoltaic solar panels can often supplement traditional power sources only up to a limited extent. The use of solar plants is totally affordable only in those cases in which primary energy consumption must necessarily be reduced, or where the electrical/thermal power distribution network is missing. Moreover, although many types of solar panels are used to produce hot and sanitary water, their high costs imply that pay-back periods are long, especially with the lack of specific government incentives.

Considering the nature of these traditional devices, storage and panel temperatures are directly related to each other, since it is possible to heat the storage only when the panel temperature is higher than storage one. This constraint represents the main limit to the thermal efficiency of the collector and, at the same time, it reduces the minimum solar radiation usable for heating, which must be high enough to compensate for heat losses towards the environment and to keep the collector at a sufficiently high temperature for the user. Indeed, if the heat is produced at excessively high temperatures, a significant part of the solar power G is lost towards the environment. On the contrary, if the temperature of the panel remains close to that of the environment, the maximum heat flux into the storage tank is obtained; though, this heat will have very low effectiveness (exergy value), since the storage temperature is low. Nevertheless, several studies and applications are available in the field of low-temperature solar water heaters [1,2], while developments are recognized in the field of solar absorption cooling plants both from the theoretical [3] and the experimental [4] point of view.

To break the link between panel and storage temperatures and to overcome the solar thermal panel limits, the insertion of a heat pump has been conceived and applied in the so called solar assisted heat pump (SAHP) device. Such systems can use traditional solar panels to pre-heat a water tank to be coupled with electrical heat pumps [5], including high temperature applications [6] and intermediate energy storage [7], or gas burners [8] or in conjunction with absorption systems. In this field, low-temperature heat source adsorption pumps [9] have been studied for specific solar assisted absorption heat pumps [10] and an updated study is available in Ref. [11]. The performance of different fluids has been explored for example in Ref. [12]. Combined air-solar and geothermal-solar sources are described in Refs. [13] and [14] also with reference to multiple heat sources [15]. Studies about modeling and optimization of solar assisted heat pump with latent heat storage material can be found in Refs. [16] and [17], while reviews on the general subject of heat pump water heating can be found in Refs. [18] and [19]. It is worth mentioning that some solar assisted heat pump hot water systems are already available in the market [20,21].

In case of small systems, the evaporator of the heat pump is integrated into the solar panel. These systems are also known as direct expansion SAHP (DX-SAHP) or as integrated SAHP (ISAHP).

The main issue addressed in this study is the presentation of an easy-to-handle thermodynamic model in view of a steady-state analysis of DX-SAHP systems. To this aim, several approaches can be envisioned. The first is to consider the actual thermodynamics associated with a simple vapor compression inverse cycle. Another is to use the performance tables and charts given by heat pump manufacturers, thus avoiding any detailed description of the refrigerant fluid thermodynamics, at the cost of developing a model which is valid only for a specific appliance.

In this study, a steady state analysis of a DX-SAHP is proposed by making use of a novel approach to express the relevant characteristics and the performance of the system as an explicit function of environmental, design and context variables. The core model is based on the inverse simplified Carnot cycle, which is fluid independent, thus avoiding the need for computationally demanding calculations of the refrigerant fluid (typically an HFC or an HFO in the future) thermophysical properties.