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Investigation of the performance of a combined solar thermal heat pump hot water system

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Abstract

The use of a heat pump as an auxiliary energy source for solar domestic hot water systems can achieve significant energy savings, due to the remarkable potential of heat pumps on the efficient provision of thermal energy. In this work, the performance of a combined solar thermal heat pump hot water system is investigated. A component based simulation model for the whole system was experimentally validated. Emphasis was paid on the formulation of a simple and efficient approach for the modeling of the heat-pump. The performance of the system on an annual basis is investigated, with regard to the methodology used in solar domestic hot water systems testing. According to the results of the analysis, the system achieves significant auxiliary energy savings, which can present a value in the order of 70% for the climatic data of Athens. The temperature set-point for the activation of the heat pump proves to be an important parameter for the performance of the system, noting that the higher the value of the set-point, the lower the efficiency of the heat pump.

Keywords: Solar thermal; Domestic hot water; Heat pump

1. Introduction

Solar domestic hot water systems are widely disseminated and successfully used all over the world. In most cases, they are combined with a conventional system in order to cope with the intermittent solar radiation on a seasonal or daily basis. Common configurations include the use of electricity as conventional source, through an electrical resistance integrated in the solar tank, however other conventional sources can also be used; the case of providing heat through a heat pump is the one to be discussed in this work.

The improvement of the efficiency of heat pump systems, together with the decrease in their cost, has led to the dissemination of these systems not only in air-conditioning applications, but also in applications such as drying (Daghigh et al., 2010) or hot water. For the case of hot water production, the condenser of the heat pump rejects heat into the storage tank. This can be performed through different configurations of the condenser, either immersed in the tank as a wrap-around coil, or externally through a water-to-working-fluid heat exchanger (Morrison et al., 2004).

A classification proposed by Hepbasli and Kalinci (2009) proposes four types of systems: Ground Source Heat Pumps (GSHPs), Air Source Heat Pumps (ASHPs), Solar Assisted HPs (SAHP) and Gas-Engine Driven Heat Pumps (GEHPs). These systems differ in the heat source used as the evaporator; this can be a ground source, ambient air, solar heat source, or even a gas engine. The condenser (or heat sink) is the hot water storage tank.

The above referenced systems, mainly concentrating in the case of SAHPs, can be characterized as integrated (Malenkovic, 2012). An alternative configuration, which is the case of the system presented in this work, refers to

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Nomenclature

A	area [m^2]
b	connecting pipe insulation thickness [m]
COP	heat pump coefficient of performance [−]
D	storage tank diameter (internal) [m]
d	connecting pipe diameter (external) [m]
E	energy [J]
ES_{aux}	auxiliary energy saving fraction of the system [−]
F	volumetric flow rate [m^3/s]
G	solar radiation flux [W/m^2]
H	incident solar energy on the collectors' surface [J]
h	storage tank height [m]
K_θ	incidence angle modifier [−]
k	connecting pipe insulation material thermal conductivity [W/m K]
L	connecting pipe length [m]
M	number of measurements [−]
$\dot{m}$	mass flow rate [kg/s]
N	number of storage tank segments [−]
P	power (electrical) [W]
$\dot{Q}$	power (thermal) [W]
$\dot{Q}_{hp,ref}$	nominal thermal load capacity of the experimental heat pump [W]
RH	relative humidity [−]
RMSE	root mean square error [units of the estimated quantity]
SPF	heat pump seasonal performance factor [−]
T	temperature [°C]
t	time [s]
U	heat loss coefficient [W/K]

Greek letters

θ	angle of incidence [°]
η	efficiency [−]
ρ	density [kg/m^3]

Subscripts

a	ambient
aux	auxiliary heating source
c	storage tank cold water inlet
cal	simulated values
cw	storage tank hydraulic circuit
d	storage tank hot water outlet
el	electrical
hx, sol	solar collectors to storage tank heat exchanger
in	inlet
out	outlet
hp	heat pump
pipe	pipe connection
s	storage tank
sol	solar collectors
tank	position in the storage tank at the inlet of the heat pump to storage tank heat exchanger
tot	total energy provided to the system by both the solar collectors and the heat pump
use	useful energy provided to the user by the system
w	water

combined systems, in the sense that the heat pump and the solar thermal subsystems do not interact, but both supply heat to the storage tank.

Heat pump hot water systems are available in the market in many countries, mainly with configurations of air-source or solar-source evaporators (Lloyd and Kerr, 2008; Morrison et al., 2004). Studies in the relevant literature concern the improvement of systems performance through the investigation of optimum operation conditions and the proposal of technological solutions or alternative configurations. Chyng et al. (2003) present a 1-year simulation analysis of an integrated solar assisted system, concentrating on the optimization of the refrigeration cycle, as well as on the behavior of the COP of the complete system. Li and Yang (2010) present a mathematical model for such a system. Minetto (2011) proposes a CO_2 refrigeration cycle, adjusted to the operation conditions relevant to the domestic hot water production. Shao et al. (2003) propose the installation of a preheater and a reheater of domestic hot water at the outlet of the compressor and the inlet of the thermal expansion valve, in order to increase the effectiveness of an air-source system.

Frank and Herkel (2010), present an approach to describe and systematically classify combined solar thermal and heat pump systems. Lloyd and Kerr (2008) present a review of respective studies for solar heaters and heat pump water heaters, including their own measurements, aiming at quantifying the energy saving potential of the discussed systems. Conclusions suggest that over a wide range of environmental temperatures there is little difference in performance between solar thermal systems that have a permanently connected electric boost backup and heat pump systems. The authors point out the ability of heat pump systems to cope with variation in draw-off times or lack of control policy on the one hand, and the ability of solar thermal systems to produce hot water without any non-environmental energy on the other. Morrison et al. (2004), through annual load cycle operation based on a combination of component testing and simulation with the TRNSYS package, concluded that air-source heat pump water heaters present lower performance than typical solar water heaters or solar boosted heat pump water heaters; one has to note though the flexibility conventional systems present when considering non-favorable sites in