Energy Conversion and Management 173 (2018) 626–639

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Energetic investigation of solar assisted heat pump underfloor heating systems with and without phase change materials

Maria T. Plytaria[*], Christos Tzivanidis, Evangelos Bellos, Kimon A. Antonopoulos

Thermal Department, School of Mechanical Engineering, National Technical University of Athens, Greece

ARTICLE INFO

Keywords:
Phase change materials
TRNSYS
Underfloor heating system
Solar assisted heat pump
Thermal photovoltaic collector
Sustainability

ABSTRACT

The application of phase change materials (PCMs) in the building envelope can improve the thermal performance and the indoor thermal comfort conditions because they allow the proper storage or release of energy. In this work, three different solar assisted heat pump underfloor heating systems with and without the use of phase change material are designed, simulated and evaluated energetically for a building of 100 m^2 floor area. Different kinds of solar collectors (flat plate, photovoltaic, thermal photovoltaic) are coupled to a storage tank which feeds a heat pump for space heating purposes. The PCM is used on the underfloor heating system in order to increase the storage capacity and to avoid the operation of the heat pump during the peak electricity demand period. Furthermore, this work presents and compares the coefficient of performance, the electricity consumption, the solar coverage and the indoor temperature distribution of a building in Athens (Greece), with and without a PCM layer on the floor. More specifically, the PCM is placed on the underfloor heating system and different cases are examined by changing the collecting area, the collector type and the thickness of the insulation layer in the floor. The results prove that the use of the PCM layer on the underfloor heating system reduces the heating load by about 40%. The electricity consumption can be reduced between 42% and 67% using the solar-driven systems. It is also found that the system with the thermal PV consumes the lowest grid electricity. Moreover, the lowest simple payback period is found to be 9.61 years for the system with flat plate collectors without PCM. The simulation is conducted with TRNSYS for all the winter period.

1. Introduction

In the last years, the energy consumption in the building sector has an increasing rate and it is close to the 40% of the worldwide energy consumption [1]. More specifically, the specific heating consumption for typical buildings varies from 15 kWh/m^2 year to 100 kWh/m^2 year [2]. The use of alternative energy sources, such as solar energy is very promising to cover partially or totally the energy demands of buildings [3]. In Greece, the solar radiation potential varies from 1400 kWh/m^2 year to 1800 kWh/m^2 year, with Athens to have an intermediate value at 1600 kWh/m^2 year [4]. This solar potential is promising for covering the heating energy needs of the Greek buildings in a great percentage. Solar energy can be utilized for domestic hot water production or for space heating applications in the building sector. Moreover, in many cases, the solar collectors are integrated with store tanks or heat pumps in solar-only or hybrid systems [5].

In literature, there are numerous studies associated with the utilization of solar energy in solar assisted systems and mainly with heat pumps [6,7]. These systems utilize mainly flat plate collectors in order to heat water in the storage tank and afterward the stored hot water is exploited as the heat source for driving the water for example to an air heat pump for heating load production. The basic advantage of this technology, compared to the conventional heat pumps, is the higher coefficient of performance (COP) due to the higher heat source temperature level [4]. In many literature studies, the use of hybrid photovoltaics or thermal photovoltaics instead of flat plate collector for assisting the heat pump has been analyzed by many researchers.

In a recent study, Bellos et al. [7] examined various combinations of solar thermal systems and heat pumps. They concluded that the electricity cost is a decision factor for the viability of every technology. Moreover, they stated that the use of thermal photovoltaic collectors is a promising technology for the future, because of the increasing rate of the electricity price. In an interesting study, Poppi et al. [8] compared solar assisted and air source heat pumps in various conditions. Moreover, Atmaca [9] examined experimentally the use of a solar assisted heat pump by the exergetic point of view and proved that this technology is suitable for locations with high solar potential. Fine et al. [10] combined a ground source heat pump system with a solar thermal array

---

[*] Corresponding author.
E-mail address: maplyt@central.ntua.gr (M.T. Plytaria).

https://doi.org/10.1016/j.enconman.2018.08.010
Received 7 June 2018; Received in revised form 11 July 2018; Accepted 4 August 2018

Nomenclature

A_c	collecting area, m^2
b	temperature coefficient of cell efficiency, K^{-1}
C	capital cost of an examined system, €
C_0	capital cost of the reference system with boiler, €
CF	yearly cash flow of an examined system, €
CF_0	yearly cash flow of the reference system with boiler, €
c_p	specific heat capacity, kJ/kg K
$c_{p,liquid}$	specific heat capacity at liquid state, kJ/kg K
$c_{p,solid}$	specific heat capacity at solid state, kJ/kg K
f	electrical solar cover, –
F′	collector fin efficiency, –
G_T	solar titled radiation, W/m^2
I	current, A
m	mass flow rate, kg/s
m_{pcm}	mass of the PCM, kg
m_{und}	mass flow rate in the underfloor system, kg/s
P_{el}	electrical production of the solar collector, kW
P_{grid}	grid electrical consumption, kW
Q	heat rate, kW
Q_{hp}	heat input in the heat pump, kW
Q_{load}	heat input in the building, kW
q_1	first logistic energy rate in TRNSYS, kW
q_2	second logistic energy rate in TRNSYS, kW
SPP	simple payback period, years
T	temperature, °C
U	thermal transmittance, W/m^2 K
V	voltage, V

Greek symbols

α	plate absorbance, –
ΔC	difference in the capital cost, €
ΔCF	yearly cash flow gain, €
ε_p	plate emittance, –
η_{el}	electrical efficiency, –
η_{th}	thermal efficiency, –
η_{tot}	total efficiency, –
τ	cover transmittance, –

Subscripts and superscripts

b	back part of the collector
c	collector
$c_{,in}$	collector inlet
$c_{,out}$	collector outlet
e	collector edge
el	electrical
hp	heat pump
liquid	liquid state
loss	thermal loss of the storage tank
max	maximum
mp	maximum power
ref	reference conditions
s	solar
solid	solid state
stored	storage tank
th	thermal
tot	total
u	useful
und	underfloor

Abbreviations

COP	coefficient of performance
FPC	flat plate collector
NOCT	nominal operating cell temperature
PCM	phase change material
PV	photovoltaic collector
PVT	thermo-photovoltaic collector
TESS	Thermal Energy System Specialists

and proved that this system is viable from a technical and economic standpoint. Liu et al. [11] developed a model of a solar absorption-subcooled compression hybrid cooling system in order to present a design principle for the nominal cooling capacity of the absorption subsystem. It is found that the size of the absorption chiller in the solar absorption-subcooled compression hybrid cooling system should be designed according to the meteorological data when the solar irradiance is at a medium level. Xu et al. [12] studied a novel solar-powered hybrid ejection compression refrigeration cycle with various refrigerants. This novel cycle was also compared with conventional ejection-compression cycle and it is found that the novel cycle has better feasibility and good energy performance. Finally, Xu et al. [13] studied a novel modified ejection-compression refrigeration cycle and they compared it with a conventional ejection-compression refrigeration cycle. Their analysis based on exergetic and economic results and proved that the novel cycle has an excellent application potential.

Phase Change Materials (PCMs) have the advantages of energy storage and can be used in buildings following different applications. For example, they can be incorporated into various building components, such as walls [14,15], floors [16,17], roofs [18] and window glazing [19,20], using micro or macro-encapsulation and thus improve the thermal performance of the building, reducing air heating or cooling requirements. Furthermore, they can be integrated into the storage devices of energy systems.

Numerical and experimental investigations with different types of PCM containers are published in several cases. Some of these types are sphere [21,22], rectangular [23] and shell and tube designs [24,25]. Furthermore, a considerable amount of literature relating to the heat transfer enhancement of PCMs for thermal energy storage applications was reviewed by Ibrahim et al. [26]. Khan et al. [27] are reviewed PCMs in solar absorption refrigeration systems. Their paper provides an overview of PCMs and their enhancement methods for absorption refrigeration system. A recent work by Safari et al. [28] has reviewed the supercooling of PCMs in thermal energy storage systems and they discussed applications with solar thermal storage. Luo et al. [29] studied a Photovoltaic (PV)-PCM system in order to control the temperature of a PV panel by applying high thermal conductive form-stable paraffin (ZDJN-28)/EG composite PCM. The results showed that compared with the temperature of the conventional PV panel, the temperature of the PV-PCM panel is kept below 50 °C with increased output power by 7.28% in the heating process. Al-Waeli et al. [30] proposed a new thermal Photovoltaic (PVT) system which consists of a tank filled with paraffin wax mixed with nano-SiC to enhance its thermal conductivity. The performance of the system was compared with other systems namely the PV plate, wax tank cooled with water, water tank cooled with water and the results showed that the proposed new system reduced the temperature of the photovoltaic cell more than other systems, especially during peak time. Nada et al. [31] investigated the thermal regulation and efficiency enhancement of PV-building integrated system using phase change materials (PCMs) and the results show that the integration of the PCM to the back side of the PV modules regulates the module temperature and improves its efficiency. Yang et al. [32] developed and validated a simplified numerical model for the currently constructed finned heat pipe assisted low melting point metal PCM heat