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Experimental investigation and feasibility analysis on a capillary radiant heating system based on solar and air source heat pump dual heat source

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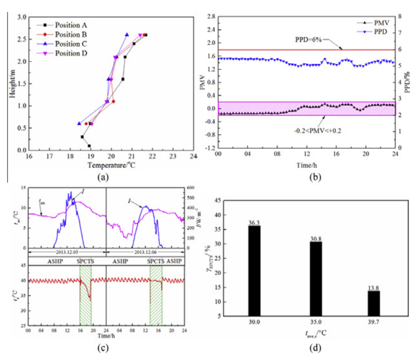
HIGHLIGHTS

- A capillary heating system based on solar and air source heat pump was developed.
- Influence of supply water temperature on solar energy saving rate was investigated.
- Heating performance and thermal comfort of capillary heating system were analyzed.
- Low temperature heating with capillary is suitable for solar heating system.

GRAPHICAL ABSTRACT

(a) Vertical temperature gradient in Case 3, (b) PMV and PPD of the test room in Case 3, (c) operating time of SPCTS and ASHP systems in Case 3 and (d) the proportion of SPCTS operating time.



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ABSTRACT

Due to sustainable development, solar energy has drawn much attention and been widely applied in buildings. However, the application of solar energy is limited because of its instability, intermittency and low energy density in winter. In order to use low density and instable solar energy source for heating and improve the utilization efficiency of solar energy, a solar phase change thermal storage (SPCTS) heating system using a radiant-capillary-terminal (RCT) to effectively match the low temperature hot water, a phase change thermal storage (PCTS) to store and continuously utilize the solar energy, and an air source heat pump (ASHP) as an alternate energy, was proposed and set up in this research. Series of experiments were conducted to obtain the relation between the solar radiation utilization rate and the heating supply temperatures, and to evaluate the performance of the RCT module and the indoor thermal environment of the system for its practical application in a residential building in the north-western City of Xi'an, China. The results show that energy saving of the solar heating system can be significantly improved by reducing the supplied water temperature, and the supplied water temperature of the RCT would be no more than 35 °C. The capillary radiation heating can adopt a lower water temperature and create a good thermal comfort environment as well. These results may lead to the development of designing and distributing the solar energy for building heating during winter.

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Nomenclature

Lain letters

f	ratio of the surface area of the clothed body to the surface of the nude body (–)
h	heat transfer coefficient (W m^{-2} K^{-1})
I	solar radiation intensity (W m^{-2})
M	metabolic rate (W m^{-2})
m	flow rate (m^3 s^{-1})
PMV	predicted mean vote (–)
PPD	predicted percentage of dissatisfied (%)
p	water vapor partial pressure (Pa)
Q	heat capacity (W)
q	heat flux (W m^{-2})
R	clothing insulation (clo, 1 clo = 0.155 m^2 °C W^{-1})
t	temperature (°C)
Δt	temperature difference (°C)
W	effective mechanical power (W m^{-2})

Subscripts

A1.6	at a height of 1.6 m for position A
A2.4	at a height of 2.4 m for position A
A2.6	at a height of 2.6 m for position A
a	air
am	ambient
ave	average
B1.6	at a height of 1.6 m for position B
C1.6	at a height of 1.6 m for position C
c	convective
cl	clothing
D1.6	at a height of 1.6 m for position D
en	envelope
max	maximum
min	minimum
r	return
ra	radiation
s	supply

Greek symbols

γ	proportion (%)
θ	time range (h)
v	velocity (m s^{-1})
τ	operating time (h)

Abbreviations

ASHP	air source heat pump
COP	coefficient of performance
HVAC	heating, ventilation, and air conditioning
PCM	phase change material
PCTS	phase change thermal storage
RCT	radiant-capillary-terminal
SPCTS	solar phase change thermal storage

1. Introduction

Due to the rising of buildings and the promoting of indoor thermal comfort, energy consumption in buildings has a large proportion in total final energy consumption. Energy consumption in buildings is responsible for 40% of global energy in EU, USA and UK [1–3]. Over one-third of China's total energy is used in buildings [4,5] and energy consumption for heating and cooling is about 63% of the overall energy consumption in buildings in China [5]. The main energy consumption in buildings in China is attributed to large and inefficient heating, ventilation, and air conditioning (HVAC) systems, especially for cooling and heating applications [6,7]. Both energy conservation and indoor thermal comfort are of main concerns for architects to select an appropriate HVAC system for their building development [8]. The progressive depletion of fossil fuels, the growing energy demand and government policies for reducing environmental pollution emissions have increased the urgency of finding alternative energy sources and technology solutions to reduce energy consumption and to use energy more efficiently. Currently, renewable energy, especially solar thermal energy is receiving much attention as an energy source option [9,10].

Among various renewable energies, solar energy has the advantages of being high potential with long sunlight hours and workable intensity and so has been widely used in energy supply for buildings in China [11]. However, solar energy is instable and intermittent due to the influences of random factors, such as available daylight hours, seasonal fluctuation, and weather change. The application of solar energy for building heating in winter is therefore restricted. In order to stably and continuously utilize the solar energy, many investigations have been carried out by combining solar energy with other energy sources and employing thermal storage [12,13], especially the phase change thermal storage (PCTS) employing a phase change material (PCM) which is an effective method due to its advantages of high energy storage density and its isothermal operating characteristics during solidification and melting processes [14]. Searle et al. [15] designed a low temperature solar heating system based on slurry PCM to improve the solar panel efficiency. Osterman et al. [16] proposed a stand-alone unit suitable for offices consisting of plates filled with paraffin PCM, and confirmed the feasibility of using the thermal energy storage system on an annual basis for cooling and heating by the simulation and experiment. As for the combination of solar energy with other energy sources, Shan et al. [17] studied solar and air source heat pump (ASHP) with a radiant floor water heating system operating within a passive house in a cold climate zone. Active solar contributed 16.8% of the total heating energy supply by calculating the heat supplied to the building during the 8 days when the average outdoor temperature and daily accumulative ambient solar radiation on vertical surfaces was −6.3 °C and 205.4 MJ. Chen et al. [18] performed an experimental analysis on a ground coupled heat pump with solar thermal collectors and fan coil for space heating. Soil and solar energy was used as heat sources at intermittent space heating for 3 days, and it was found that the daily solar fraction of the system reached up to 0.53 when the average solar radiation of the sampled heating session was 692.52 W m^{-2}.

However, Solar energy generally has a relatively low energy density and heat flux, particularly in winter. Moreover, the efficiency of using solar energy is greatly limited by the supplied water temperature, and the solar energy efficiency decreases with an increase in supplied temperature [19]. Therefore, reducing the supplied water temperature is an important factor to improve the utilization efficiency of solar energy, especially, for solar heating in winter. The conventional heating forms would require relatively higher supplied water temperature. Some studies on supply and return water temperature for different heating system such as radiant floor, radiant ceiling, and radiator heating are summarized in Table 1. The radiant-capillary-terminal (RCT) heating, a new way