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Design and performance of the solar-powered floor heating system in a green building

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ABSTRACT

In the green building of Shanghai Research Institute of Building Science, the evacuated tubular solar collectors with a total area of 150 m^2 were installed to provide heating for the covered area of 460 m^2. The floor heating coil pipes were made of high-quality pure copper with the dimension of Φ 12 $\times$ 0.7 mm. Under typical weather condition of Shanghai, the average heating capacity was 25.04 kW during the working hours from 9:00 to 17:00, which was sufficient to keep indoor thermal environment. The average electric COP of the floor heating system was 19.76 during the system operation. Compared with the widely used air-source heat pump heating systems with the electric COP of 3.5 in Shanghai, the solar-powered floor heating system shows great potential in energy conservation in winter. With respect to the whole heating period, the solar fraction was 56%. According to the performance analysis of the system with ambient parameters, it was observed that the system performance could be greatly enhanced with the increase of daily solar insolation. However, the system performance varied slightly with average ambient temperature. Compared with average ambient temperature, daily solar insolation had a more distinct influence on the performance of the solar-powered floor heating system.

1. Introduction

Floor heating systems are becoming increasingly popular due to the fact that they may provide a more comfortable indoor thermal environment than convective heating systems. Furthermore, the floor heating systems provide a good compromise between energy consumption and thermal comfort [1].

Some papers concerning numerical analysis of floor heating systems have been reported. Alkhalaileh et al. presented a one-dimensional numerical model, which was used to simulate and analyze the performance of a solar pond floor heating system [2]. Ho et al. developed a two-dimensional numerical model for a hydronic heating panel, which was capable of predicting both steady state temperature profiles and transient responses [3]. Weitzmann et al. presented a two-dimensional dynamic simulation model for the heat loss and temperature distribution in a slab-on-grade floor with floor heating. The model could be used to design energy efficient houses with floor heating, focusing on the heat loss through the floor construction and foundation [4]. Athienitis and Chen employed a three-dimensional explicit finite differential model to determine the temperature distribution for a floor with radiant heating and non-uniform solar radiation incident on it. It was shown that the solar energy absorption by the thermal mass of a floor heating system might contribute to a significant reduction in energy consumption [5]. Golebiowski and Kwieckowski investigated the dynamics of the three-dimensional temperature field in the system with a direct floor heater, and analyzed the transient temperature distribution [6].

With regard to the heat sources of floor heating systems, Hamada et al. described a floor heating system driven by a ground source heat pump. It was shown that the COP of the system was 4.0. The primary energy reduction rate relative to a conventional boiler heating system was 34% [7]. Sakellari and Lundqvist made use of the computational tools TRANSYS and EES to model and analyze the performance of a residential house. The ventilation system and the floor heating system of this house were based on an exhaust air heat pump [8]. Yeo et al. reported that two types of heating production and supply systems were generally used for the hot water floor heating systems in Korea. One was the central system that supplied hot water from a central boiler or a district heating plant, covering multiple block of apartment housing. The other was the individual system using a gas-fired boiler installed in each housing unit [9].

Generally, the supply water temperature of floor heating systems is relatively lower, which leads to the feasibility of

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Nomenclature

A	area (m^2)
COP	system efficiency
C_p	specific heat of water (J/kg °C)
$D1$	duration of the solar collecting system operation (s)
$D2$	duration of the floor heating system operation (s)
$D3$	duration of sunshine (s)
F_i^C	collector control function
F_i^L	load return control function
I	solar radiant intensity (W/m)
m	mass flow rate (kg/s)
N	number of nodes
Q	heat quantity (kW)
T	temperature (°C)
U	heat loss coefficient (W/m^2 °C)

Greek symbols

ρ	density (kg/m^3)
η	solar collecting efficiency
Δm	net flow between nodes (kg/s)
Δx	distance between nodes (m)

Subscripts

a	ambient
air	indoor air
ave	average
c	solar collector
fl	floor
h	heating
hp	heat pipe evacuated tubular solar collector
hw	hot water
i	node
nh	non-heating
o	outlet
se	section
si	side
solar	solar
ta	tank
U	U-type evacuated tubular solar collector
w	water

low-grade heat sources. Solar-powered floor heating systems have been regarded as appropriate choices in solar thermal utilization projects because solar energy is characteristic of low density of heat flow rate. Besides, it is difficult for the ordinary solar collectors on the market to attain high working temperature.

Kuang and Wang reported the experimental results of a floor heating system driven by a direct-expansion solar assisted heat pump (DX-SAHP) system. The daily-averaged heat pump COP varied from 2.6 to 3.3, while the system COP ranged from 2.1 to 2.7 [10]. Argiriou et al. used TRANSYS to simulate a floor heating system driven by a solar assisted absorption heat pump (AHP). The estimated energy savings against a conventional heating installation using a compression type heat pump was in the range of 20–27% [11]. Alkhalaileh et al. presented a solar pond floor heating system. A developed computer simulation was utilized to study the potential of using such a system under the climate conditions of Jordan. It was found that the solar pond heating system could meet most of the winter season in Jordan with the solar fraction in the range of 80–100% for at least 2 months of the season [2]. Badran and Hamdan carried out theoretical and experimental investigations for two types of floor heating system powered by a solar collector array and a solar pond, respectively. It was concluded that the solar collector system was 7% more efficient than the solar pond system. Economic analysis showed that the solar collector system would break even earlier than the solar pond system. Practical considerations showed that the solar collector system required less operation and maintenance work [12]. Martínez et al. reported a solar-powered floor heating system with a heat pump as the auxiliary heat source. Under the weather condition of Murcia (Spain), the solar fractions registered during the months of January and February at the system were 0.428 and 0.342, respectively [13].

Among the aforementioned investigations, few reports have been concerned with detailed experimental study of solar-powered floor heating systems. In this paper, a solar-powered floor heating system was designed. The operation characteristics under typical weather condition of Shanghai were analyzed. Besides, the system performance was analyzed based on ambient parameters. The research work of this paper was done in Shanghai. However, it is contributive to the design and operation of solar-powered floor heating systems in other areas. The design method and the control strategy introduced in this paper were instructional for the design of solar-powered floor heating systems. The experimental investigation indicated typical operating characteristics of the solar-powered floor heating system. Besides, the potential of energy conservation for such a system was evident through the analysis of system efficiency (COP).

2. Design of the solar-powered floor heating system

2.1. Integration of solar collectors on the green building

Two solar collector types with a total area of 150 m^2 were installed on the roof of the green building of Shanghai Research Institute of Building Science. The solar collectors acted as the thermal source for the solar-powered floor heating system. The 90 m^2 U-type evacuated tubular solar collectors with CPC were placed on the west side, and the other 60 m^2 heat pipe evacuated tubular solar collectors on the east side. The two solar collector arrays were connected in parallel. The roof structure of the building was made of steel, and had been designed to face south, tilted at 40° to the horizontal ground surface. The solar collectors were mounted and integrated with the building perfectly as shown in Fig. 1.

2.2. Design of the solar-powered floor heating system

The system design was based on the heating load calculation results of Shanghai Research Institute of Building Science. The heating load of the involved area (460 m^2) was 25 kW. Except for solar collectors, the system mainly consisted of floor heating coil pipes and circulating pumps. Besides, a heat storage water tank of 2.5 m^3 in volume was employed to collect solar heat, thereby providing hot water for the solar-powered floor heating system. The flow diagram of the solar-powered floor heating system is shown in Fig. 2, where Pump 1 and Pump 2 are for the solar collecting loop and floor heating loop, respectively.

In this project, the cuprotherm floor heating system produced by Wieland Ltd. of Shanghai was chosen. Fig. 3 shows the arrangement of floor heating coil pipes. The floor heating coil pipes were made of high-quality pure copper with the dimension of Φ 12 × 0.7 mm. They were fixed on the 30 mm thick polystyrene insulation layer with spacing interval of 200 mm. And then the crushed stone concrete was poured with the thickness of 70 mm.