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The applicability of the wall implanted with heat pipes in winter of China

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ABSTRACT

The outside surfaces of south and west outer walls can absorb a large amount of solar energy in winter, which is very difficult to be directly used for space heating due to larger thermal resistance of the wall. The wall implanted with heat pipes (WIHP), as a new type of passive solar utilization technology, can make good use of the heat absorbed by the outside surface of wall. In this paper, the applicability of the WIHP in winter was studied by calculating and analyzing the working hours and heat transfer capacity of the south and west WIHPs in different districts, and the working temperature in Beijing was calculated to analyze the heat transfer performance at different time. The results show that the south WIHP is with more working hours, larger heat transfer capacity and higher energy saving rate, which can be used in the 93.63% of heating areas. The working time of the west WIHP is postponed compared with the south WIHP, so the west WIHP can only be used in specific districts. Moreover, combining the west and south WIHPs can suggest better performances, which can be popularized in engineering applications.

1. Introduction

Solar radiation is the main energy source in the world. For example, China embraces sufficient solar energy, and the yearly total solar energy can be up to 5×10^{19} kJ, with the annual mean intensity of solar radiation of 3350–8370 MJ/m^2. More than two-thirds of the country's land has the annual sunshine time of larger than 2000 h. Hence, many studies have been carried on the use of solar energy for space heating. Martínez et al. [1] and Zhao et al. [2] did experiments to study a solar radiant floor heating system to improve the utilization of solar energy. Susheela et al. [3] studied a heat pipe augmented passive solar system for space heating by means of natural convection. Trillat-Berdal et al. [4], Esen [5] Ozgener [6] and Wang et al. [7] carried on experimental study on the solar heating system with the help of heat pump. Cui et al. [8] and Chen et al. [9] evaluated a novel solar heating system with coupled solar Kang and Trombe wall. Zhai et al. [10,11] studied a solar energy system capable of heating, cooling, natural ventilation and hot water supply system in Shanghai Research Institute of Building Science. Qu et al. [12] studied a solar thermal cooling and heating system to deal with how solar energy might most effectively be used in supplying energy for a building. Zhu et al. [13] researched a new building envelope to directly utilize low-grade energy sources to reduce building cooling/heating load and improve the indoor thermal comfort.

As the basic structure of building, wall, is a key factor of energy consumption of buildings [14–19]. In the winter of Northern China, due to the dry climate, sufficient sunlight, low solar altitude, the south external wall can absorb a large amount of solar radiation. Because of the wall thermal resistance, the solar radiation absorbed by the outside surface cannot be transferred into the interior of the building effectively [20–22]. Wang et al. [23] studied a passive solar house with water thermal storage wall. Xiao et al. [24] analyzed the optimization of the interior PCM for energy storage in a lightweight wall to improve the passive solar utilization. Xu et al. [25] put forward a shape-stabilized PCM floor to absorb the solar radiation in the daytime and release the heat at night in winter. Zhang et al. [17] selected the thermophysical properties of the building envelope material through modeling and simulation for free heating. Shen et al. [26] evaluated the thermal performances of passive solar systems by the method of the finite differences and TRNSYS simulation. Zhang et al. [27] developed a numerical model to investigate the thermal response of the brick wall filled with phase change materials based on the enthalpy-porosity. Yang et al. [28] discussed the thermal performance of heat collection, the heat preservation, the heat insulation, the pre-heating of a reformative solar wall for integrating solar and thermal energy. Fang et al. [29] investigated a lattice passive solar heating wall to remarkably improve the heating performance of passive solar heated buildings.

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Nomenclature

a	solar radiation absorptivity
A	area (m^2)
Ac	cross-sectional area (m^2)
h	heat transfer coefficient [W/(m^2 °C)]
I	global solar irradiance (W/m^2)
K	coefficient of heat transfer [W/(m^2 °C)]
q	heat flux (W/m^2)
Q	heat transfer capacity (W)
t	Centigrade temperature (°C)
T	Kelvin temperature (K)
x	angle coefficient

Greek symbols

σ	Stefan–Boltzmann constant [W/(m^2 K^4)]
ε	blackness

Subscripts

ah	all of the heat pipes
air	outdoor air
a,in	indoor air
B	atmospheric long-wave radiation
ca	convection to environment
ci	convection of wall inside surface
eq	equivalent
g	ground thermal radiation
h	heat pipe
in	inside surface of wall
j	serial number of indoor surface
m	number of indoor surfaces
out	outside surface of wall
R	ground long-wave radiation
ra	radiation to environment
ri	radiation of wall inside surface
s	solar radiation
sa	solar-air
shw	short-wave radiation
t	total
ti	transfer to indoor
w	wall except heat pipes

Acronyms

PCM	phase change material
WIHP	wall implanted with heat pipes

To solve the above problems, the author combined the gravity heat pipe with wall to construct a new type of passive solar energy utilization technology, the wall implanted with heat pipes (WIHP) [30]. The WIHP uses the high efficient heat transfer performance, one-way thermal conductivity and thermal switch [31–34] of gravity heat pipes to transfer the heat into the indoor in winter and transition seasons, or to transfer the excess heat to outdoor in summer and transition seasons under certain conditions. In this paper, the applicability of the WIHP in winter is researched by analyzing the heat transfer performances and the working hours of the WIHP in all heating areas and part areas without heating in China.

2. Structure and working principle

The WIHP combines heat pipes and the automatic control with the wall thermal insulation technology to form a new passive composite wall with phase-change, heat storage, and heat release. The structure and working principle of the WIHP are shown in Fig. 1 [30]. The WIHP is constructed by implanting the micro gravity heat pipes in millimeter level [35] on the basis of the common wall, and achieves the regulation of indoor thermal environment throughout the year by automatic adjusting the intelligent valves on the south, west and north external walls. The detailed structure and working principle are illustrated in reference [30].

3. Heat transfer process

Fig. 2 is the heat transfer process of the WIHP in winter, and it can be divided into five stages:

(1) The heat transfer progress between outdoor environment and the outside surface of WIHP includes the heat transfer between the outdoor environment and outside surface in the form of heat radiation and heat convection.
(2) The heat transfer progress between the wall and the working medium in the evaporating section of heat pipes includes heat conduction between the surface of the WIHP and the wall of heat pipes and heat exchanging between the wall of heat pipes and the working medium.
(3) The heat pipes transfer heat from the evaporating section to the condensing section.
(4) The heat transfer progress between the working medium in the condensing section and the wall of heat pipes includes heat exchanging between the wall of heat pipes and the working medium and heat conduction between the surface of the WIHP and the wall of heat pipes.
(5) The heat transfer progress between the inside surface of WIHP and indoor environment includes the heat exchanging between the inside surface and indoor environment in the form of heat radiation and heat convection.

The outside surface of the WIHP is influenced by many factors, and the heat balance can be expressed as follows:

$$q_S + q_R + q_B + q_g = q_{ti} + q_{ca} + q_{ra} \tag{1}$$

where q_s, q_R, q_B, q_g represent the solar radiation, ground long-wave radiation, atmospheric long-wave radiation, ground thermal radiation accepted by the per unit area of outside surface, respectively; q_{ti} is the heat transfer to indoor by the per unit area of the WIHP; q_{ca} and q_{ra} are the convective and radiate heat transfer by the per unit area of outside surface to the surrounding environment.

In order to analyze the comprehensive thermal effect of the outdoor air temperature, the solar radiation, the ground reflection radiation, the ground and atmospheric long wave radiation on the outside surface of the WIHP, the solar-air temperature, is put forward on the basis that the outdoor air temperature increases the equivalent temperature of a solar radiation. The equation is as follows [27]:

$$t_{sa} = t_{air} + \frac{aI}{h_{out}} \tag{2}$$

where I is the global solar irradiance, including the direct solar radiation and sky radiation, h_{out} is the heat transfer coefficient for heat radiation and convection.

The heat transfer progress of the WIHP can be simplified that the heat is transferred by wall and heat pipes, respectively. The heat pipes are equivalent to the thermal bridge. The equivalent heat transfer coefficient (EHTC) of the WIHP is expressed by the following equation [30]:

$$k_{eq} = \frac{k_w A_w + k_h Ac_{ah}}{A_t} \tag{3}$$

where A_w is the area of wall, Ac_{ah} is the cross-sectional area of through-wall heat pipes, A_t is the sum of A_w and Ac_{ah}.