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Energy saving effect of air circulation heat storage system using natural energy

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ABSTRACT

A central air circulation system that uses a roof ventilation layer and a phase change material (PCM) unit is proposed as a possible means of controlling thermal load and peak load. The central air-conditioning air-circulation-type system enables reduction of sensible heat load and facilitates radiative cooling/forced heat exchange in summer, and solar heat collection in winter, via the roof ventilation layer; thereby improving efficiency. The PCM unit is incorporated into the air circulation route to store the cold energy of the cooled air by radiative cooling and the heat energy of the heated air by solar heat collection. The actual measurement results of an experimental house were analyzed and numerical simulations were performed to evaluate the effective sensible heat and peak load reductions. The quantitative simulation and experimental results indicate that significant sensible heat reduction can be achieved by employing the proposed system, which uses natural energy to reduce the energy consumption of indoor temperature control.

1. Introduction

The energy consumed by housing and buildings accounts for more than 30% of the energy consumption in Japan. There has been a remarkable increase in energy consumption and CO_2 emissions in recent decades, and this will have to be reversed in order to realize a low-carbon society. Thus, further strengthening of energy conservation measures is required [1]. A policy was recently established that obliges all new housing and buildings to conform to energy conservation standards by 2020 in Japan. It also aims to achieve a 10% increase in the proportion of renewable energy per primary energy supply by 2020, through the promotion of solar light and solar heat [1]. However, compared with solar power generation, the use of solar heat has been pointed out as having low economic efficiency and high equipment cost, and its development as a system has been comparatively slow; consequently, its adoption has been stagnant [2].

In order to reduce energy consumption and improve the thermal comfort of residents, insulated and airtight houses have become a rising trend, and it is expected that duct-type whole-building air-conditioning systems that integrate ventilation, cooling, and heating will be extensively adopted. This type of system very effectively ensures the thermal comfort and health of the indoor environment, a thermal barrier-free living environment, and acts as a countermeasure for unhealthy indoor environments by using continuous forced ventilation. However, because it increases energy consumption compared with conventional individual air-conditioning systems, the system's air-conditioning performance and efficiency need to be improved [3,4].

An air-heat-collecting solar house is a good example of a house that utilizes solar heat. In its standard operation during winter, this system takes outside air from the eaves and sends heated air under the floor via an air-blown solar heat collector on the roof surface. Then, the heat from the air is stored by the foundation concrete under the floor and blown into the inside of the rooms. When sufficient solar radiation cannot be obtained on the roof surface, auxiliary heat sources and auxiliary heating under the floor are operated [5]. However, in this system, individual control of each room is difficult, and problems exist such as the inability to fully utilize the solar energy because of phenomena such as overheating during the day and room temperature reductions at night [6].

The temperature of building envelopes such as the roof and façade also increases because of the increase in incident solar radiation. The absorbed solar heat can be transferred by forced

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airflow or natural convection using a ventilation layer in the building envelope component. In previous studies, experimental and simulated results indicated that ventilated roof components can provide beneficial solar cooling [7–11]. Lee et al. [12] conducted an experimental study to evaluate and improve the cooling effect of ventilation in the cavity of metal roofs and confirmed that factors such as roof angle and the shape of the roof cavity are related to the heating effect by using a roof simulator. However, it is necessary to consider solar energy in winter and hybrid system development with other passive systems. In addition, studies in which such systems are implemented in real houses over long periods are required.

A latent heat storage (LHS) material, commonly called a phase change material (PCM), is a heat storage material that utilizes latent heat (heat absorption during melting/heat release during solidification) when a substance undergoes a phase change from solid to liquid or from liquid to solid. Many studies of thermal storage and cold storage by LHS technologies that use PCMs have been previously reported. In a review, Mavrigiannaki and Ampatzi [13] examined the properties and contextual performance factors of LHS systems. However, many studies that only integrate them into walls, floors, ceilings, or materials thereof, in order to have them incorporated as building elements, have been conducted, resulting in only a small heat storage capacity relative to the building volume.

Laoudi and Lacroix [14] evaluated the heat storage performance of a ventilated panel-heating unit by radiation and convection. They concluded that large values of PCM convection coefficients or low values of radiation coefficients substantially increase the discharge time of the latent heat energy. Butala and Stritih [15] further investigated PCM cold storage by convection. They calculated the cold storage and air cooling time for a variety of velocities and inlet air temperatures; however, integration into building structures is necessary for further development of cold storage by convection. Takeda et al. [16] proposed a ventilation system that utilizes thermal energy storage using PCM granules and performed column experiments and computer simulations. Because PCM granules consist of PCM and granulated porous media, it is possible to install a PCM-packed bed into an air supply duct.

In this study, the following activities were carried out:

(1) A central air-conditioning air-circulation-type system that utilizes direct current fans was employed in an air-conditioning room. This system was designed to reduce heating and cooling energy and individually control the blast volume in each room
(2) An air-circulation system using a roof ventilation layer, which performs radiation cooling/heat exhaust in summer and solar heat collection in winter by air circulation of the roof ventilation layer, was applied in the central air-conditioning system of an experimental house. It is believed that this system can be introduced into the ventilation layer of conventional houses.
(3) A PCM unit with sufficient LHS capacity was incorporated into the air circulation system of the experimental house to regulate the temperature and to reduce the peak load in every air-conditioned room.
(4) The temperature stabilization effects of the PCM box by air convection were verified through laboratory experiments, and its thermal regulation performance was validated by actual measurement and numerical simulation. The total sensible heat reduction of the building was evaluated based on the results.

Integration of this central air circulation system, roof ventilation layer, and PCM can promote energy efficiency and reduce sensible heat load and peak load in both summer and winter.

2. Overview of the experimental house and its air-conditioning system

2.1. Experimental house

Fig. 1 and Table 1 respectively show the exterior of the experimental house (located in Yufuin, Oita prefecture, Japan) and its specifications. Fig. 2 and Fig. 3 show the floor plans and the cross section of the roof, respectively, and temperature measurement points. Measurement of thermal environments such as the internal temperature of the roof ventilation layer (eaves, center, ridge), indoor temperature and humidity, internal wall temperature and humidity, and external weather was performed.

2.2. The air circulation system

2.2.1. Central air-conditioning air circulation type system

In the experimental house, a central air-conditioning air-circulation-type system was adopted. A schematic diagram of this system is shown in Fig. 4. An air-conditioning room that utilized a heat pump air conditioner for domestic use with 24-h ventilation by a total heat exchanger was setup. In this air-conditioning room, the outside air was introduced to the total heat exchanger, and conditioned air then blown to each room through ducts. For air circulation, a DC motor fan that is capable of low-load operation was adopted. In addition, because the air in each room circulated through the ducts, corridor, etc., to the air-conditioning room, it functioned as an air-conditioning system integrating ventilation and air conditioning. In the summer, outside air was taken in through the roof ventilation layer and discharged to the outside as it is, thereby preventing high temperatures inside the roof aeration layer and reducing the amount of heat transmitted into the room. Air circulation was operated by temperature control, with the fan automatically operating when the temperature inside the roof ventilation layer at the center of the roof was 25 °C or higher. In winter, solar heat was collected by circulating the air between the room and the roof ventilation layer. The detailed air circulation routes in the roof ventilation layer are described in Section 3.

Fig. 1. The experimental house.

Table 1
Specifications for the experimental house.

Total floor area	235.61 m^2
Area classification	Area 5
Annual insolation area classification	A3
Insolation area classification	H2
Mean heat transmission coefficient of external wall	0.34/(m^2 K)