Smart passive system for dehumidification, cooling, and heating utilizing renewable energy in detached house

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Abstract

A smart skin system is proposed for passive dehumidification in summer and solar heat collection in winter. To reduce the heat load, an efficient air conditioning system was developed in the roof ventilation layer that separates latent and sensible heat using fibrous insulation materials with moisture conditioning properties. The potential-based principle of this system is based on non-equivalent thermodynamics. Performance and thermal load reduction were demonstrated in a detached house using a heat, air, and moisture (HAM) simulation software called THERB for HAM. This system can reduce 80% of latent heat load in summer and 30% of sensible heat load in winter.

Introduction

Energy consumed in the household sector usually accounts for 30% of the energy consumption of the entire house. However, in recent years, energy consumption trended to decrease due to individual energy savings and development of new energy-efficient technologies. Nevertheless, 30% of residential energy consumed in Japan is used for cooling and heating (Agency for Natural Resources and Energy at METI, 2016). Furthermore, it is obligatory for all new houses and buildings to conform to the energy conservation standards by 2020 (Agency of Natural Resources and Energy, Energy Conservation and Renewable Energy Department in Japan, 2011).

The climate of Japan differs from region to region, but is generally hot and humid in summer months and cold and dry in winter months. Domestic heat pump air-conditioner system and dehumidifiers are used to dehumidify air during summer. However, air-conditioner equipment has high running costs and energy consumption, and heating using the air conditioner during winter can cause over-dry indoor environment. Moreover, recent high-efficiency air-conditioners perform cooling by keeping relatively high temperature refrigerant compared with conventional equipment in order to reduce energy consumption, which can weaken the dehumidifying effect. Several studies have reported the effects of passive dehumidification using solar heat, but suggest that the moisture capacity of houses should be increased (Parker et al, 2008), (Areemitt, Sakamoto, 2007). The research on passive house using solar radiation heat through air circulation has been actively reported, but it is not enough for houses that are

designed and analyzed considering both heat and humidity (Ibañez-Puy M., et al, 2017).

In this paper, we propose an intelligent building skin system that can perform passive dehumidification and radiative cooling in summer and solar heat collection and humidity control in winter using air circulation in the roof ventilation layer and utilizing solar heat. A highly efficient air conditioning system that separates latent and sensible heat was developed using fibrous insulation with excellent humidity control. Based on numerical analysis, we aimed to develop an intelligent building skin system able to reduce the heat load of the entire building. We plan to use the results of this study to investigate the actual application and optimization of this system for real houses.

Smart building skin system

In our previous research, the basic principles of passive dehumidification in summer were explained using the theory and the effects of the system and were verified through laboratory experiments and numerical simulation (Lee et al, 2017). The laboratory experiment was conducted using a model of a roof, and the heat and moisture transfer is theoretically analyzed and the parameters (flow rate, length of ventilation layer, moisture capacity, etc.) affecting the dehumidifying effect were examined

In this paper, we aimed to apply the proposed system to actual houses based on the fundamental results of the previous research. The fundamental principle is reiterated to understand the summer mode of the system (passive dehumidification). Moreover, solar heat collection and humidity control principle, which is the main function of the winter mode, is further explained.

Driving force of water vapor: Water potential

The thermodynamic equilibrium condition occurs when temperature, pressure, and chemical potential of each component are uniform. In a non-equilibrium state, the matter flows towards a lower chemical potential (substances move if there is no chemical change). This chemical potential is applied to 1 kg of water vapor as an index of mass equilibrium condition: water potential. Water potential is a type of non-equilibrium thermodynamic energy that is a function of water vapor concentration, the internal energy of water vapor molecules, the force acting on the water vapor molecules (adhesive power or capillary action), and field energy (stresses such as external forces) (Ozaki et al, 2001). Thus,

water potential gradient is the driving force of moisture flux. It enables the combined analysis of heat and moisture movement in this system. Figure 1 shows the relation between water potential (μ_w), temperature (T), and humidity. Water potential at a certain temperature and humidity is the sum of the saturated water potential (μ_w^0) and the unsaturated water potential (μ). The basic thermodynamic principles are defined in (1) – (3):

$$\mu_w(p, T) = \mu_w^0(T) + \mu(p, T) \quad (1)$$

$$\mu_w^0(T) = 6.44243 \times 10^5 + c_{p, w_{kg}} (T - 273.15) - T c_{p, w_{kg}} \ln \frac{T}{273.15} + R_w T \ln \frac{p_s}{1.01325 \times 10^5} \quad (2)$$

$$\mu(p, T) = R_{w_{kg}} T \ln \frac{p_w}{p_s} \quad (3)$$

where $c_{p, w}$ is the specific heat, expressed in units of J/(kg K); p_w is the vapor pressure of the humid air; p_s is the saturated vapor pressure at temperature T ; and $R_w = 461.50$ [J/(kg K)], calculated by dividing the gas constant $R = 8.31441$ [J/(mol K)] by the molecular weight of water 18.016×10^{-3} [kg/mol].

$$\mu_w = \mu_w^0 + \mu$$

Figure 1: Water potential, temperature and humidity.

Function of summer mode: Dehumidification and radiative cooling

Figure 2 shows the changes in the temperature, humidity, and water potential of the ventilation layer in the roof that is filled with fibrous insulation material with high water capacity. The initial indoor condition is assumed to be 24 h air conditioning for cooling at a temperature of 27°C and a relative humidity of 60%.

[Passive dehumidification during the daytime]

- A: The ventilation layer temperature increase due to solar radiation heat during daytime. (e.g. 27°C → 40°C, ① → ②)

(a) Cycle of temperature, humidity, and water potential in ventilation layer

(b) Moisture movement and exhaust in the daytime (passive dehumidification)

(c) Moisture adsorption at night

Figure 2: Cycle of moisture movement during summer.

- **B:** Water vapor from the fibrous insulation material is desorbed and diffused due to A. If the advection by air circulation (marked C) in the ventilation layer is ignored, the absolute humidity inside the ventilation layer increases to the same level as that in the heat insulation (①→②).
- **C:** When the indoor air is circulated into the ventilation layer, the absolute humidity in the ventilation layer decreases close to the absolute humidity of the indoor air (②→③).
- **D:** As a result of C, a difference in water potential (between ① and ③) occurs between the room and the inside of the ventilation layer. Therefore, moisture transfers from the room to the ventilation layer.
- **E:** The air containing moisture in the ventilation layer is exhausted to the outside by air circulation marked C, the dehumidifying effect can be obtained in the indoor space during the daytime.

[Dehumidification by moisture adsorption during the night time]

- **F:** The ventilation layer temperature decrease by the temperature of the outside air decreases.
- **G:** The heat insulation material adsorbs moisture, and the absolute humidity inside the wall, which includes the air ventilation layer, decreases (3→4). Furthermore, the water potential within the wall is maintained lower than in the room.
- **H:** Water vapor from the room enters the interior of the wall due to the water potential difference (between 1 and 4), but the absolute humidity gradually increases with time (4→1).
- **I:** The air in the ventilation layer is returned to the room, which enables cooling by radiative cooling and dehumidification by moisture adsorption.

In the periodic steady state of one-day cycle, the above process is repeated. Due to the solar radiation received during the day and the air circulation layer of indoor air into the ventilation layer, moisture is discharged from inside the wall to outside, allowing moisture permeation during the all day from the room to the inside of the wall.

Function of winter mode: Solar heat collection and humidity control

Although the indoor temperature and humidity (assumed to be 20°C and 50%) and the wall temperature and humidity distribution in winter are different from those in summer, the water potential difference follows the same pattern.

- **A:** The ventilation layer temperature increase due to solar radiation heat during daytime (e.g. 27°C→40°C, ①→②).
- **B:** Water vapor from the fibrous insulation material is desorbed and diffused due to A.
- **C:** The warm and humid air in the ventilation layer is circulated to the room.
- **D:** The ventilation layer temperature decrease by the temperature of the outside air decreases

(a) Cycle of temperature, humidity, and water potential in ventilation layer

(b) Advection and moisture flow during daytime

(c) Moisture flow at night

Figure 3: Cycle of moisture movement during winter.

- E : Water vapor in the ventilation layer is adsorbed to the fibrous insulation due to ventilation layer temperature decrease (③→④).
- F : Water vapor in the room is adsorbed to the fibrous material.

The periodic moisture flow phenomenon occurs within a one day cycle from the interior to the inside of the wall, and from the inside of the wall to the ventilation layer.

System configuration and air circulation routes

Passive dehumidification in summer

Figure 4(a) shows the air circulation route for the passive dehumidification during daytime in summer. During daytime, the roof ventilation layer temperature increases due to solar radiation. Therefore, moisture desorption occurs from the fibrous insulation material to the ventilation layer, and the temperature and humidity inside the ventilation layer increases.

(1): When the air temperature of the roof ventilation layer is higher than the set temperature (for example, 27°C), the fan A operates to take the indoor air into the roof ventilation layer and exhaust the air to the outdoor via the fan unit.

(2): When the indoor air passes through the roof ventilation layer, although the indoor and roof ventilation layers become equal absolute humidity conditions, the water potential of the roof ventilation layer is lower than that of the room. Therefore, moisture transfer to the roof ventilation layer.

(3): Exhausting the ventilation layer air outdoor may reduce the increase of the room temperature and dehumidify the indoor space simultaneously.

(4): Furthermore, the fan A and C operate together and the dehumidified air in the attic space is sent to the indoor staircase. Therefore, the effect of reducing the latent heat load in the house may be expected.

(5): The operation of fan C promotes the circulation of indoor air to the attic space. Therefore, the air, which is sucked into the roof ventilation layer from the indoor space, and the air in the attic space become identical.

(6): When the air conditioner installed in the attic is activated, in addition to the function of Fan C, the entire interior space has passive dehumidification effect.

Radiative cooling in summer

Figure 4(b) shows the air circulation route in the radiative cooling mode during night in summer. During nighttime, the roof ventilation layer temperature is decreased due to radiative cooling.

(1): When the air temperature of the roof ventilation layer is lower than the set temperature (for example 23°C), the fan B operates and the room air is taken into the roof ventilation layer.

(2): The air circulated in the ventilation layer is cooled by radiative cooling and dehumidified by moisture

Figure 4: Diagram of the summer and winter system:
(a) summer/day mode, (b) summer/night mode, and
(c) winter/day mode.

adsorption to fibrous insulation material due to outside air temperature decrease.

(3): The cooled and dehumidified air in the ventilation layer returns to the room, which reduce the sensible and latent heat load.

(4): When the air conditioner installed in the attic is activated, the air, which is cooled and dehumidified, is air-conditioned and circulated to the entire indoor space, therefore all interior spaces can achieve radiative cooling and dehumidification effects.

Solar heat collection in winter

Figure 4(c) shows the air circulation route of the solar heat collection mode during daytime in winter. During daytime, the temperature of the roof ventilation layer is expected to increase due to solar radiation.

(1): When the roof ventilation layer temperature is equal to or higher than the set temperature (for example, 30°C), the fan B operates to take room air into the roof ventilation layer.

(2): The air circulated in the ventilation layer is heated by solar radiation heat.

(3): The heated air is returned to the room through the fan unit, thus the sensible heat load is reduced

(4): When the air conditioner installed in the attic is activated, through the air conditioner, the heated air is blown into the entire interior space, and all interior space gets solar heat collection and heating effect.

Humidity control in winter

In winter, the water potential difference between the interior and the inside of the wall is low. Therefore, the moisture flux is lower in winter than in summer. During daytime in winter, the indoor air is sucked into the ventilation layer, and the ventilation layer air is circulated into the room. The indoor humidity is kept constant because the water vapor, which transmits from the room to the ventilation layer and returns to the room. Because the water vapor retention inside the roof is suppressed by the air circulation during daytime, internal condensation, that is a concern in the winter season, is prevented. Moreover, when moisture generated indoors is stored in the fibrous insulation at night, moisture content is desorbed due to solar radiation received during daytime. Therefore, it is possible to adjust the humidity in a room that is easy to dry in the heating period.

Heat load reduction of housing model

Calculation parameters and conditions

Figures 5 and 6 show the house model plan and the elevation. Table 1 shows the roof and wall composition of the house model and Table 2 shows physical properties of fibrous insulation for simulation. This house model adopts roof insulation. In order to arrange facilities related to the central air conditioning and air circulation systems, an attic space was set up. The roof in which the system was introduced is indicated by the red broken line in the elevation. Numerical analysis using THERB for HAM (Ozaki et al, 2005), a coupled analysis software for heat, moisture, and air, examined the reduction of heat load during summer and winter in the house model. The water potential required based on thermodynamics was used as the driving force of the moisture flow, and it was calculated as a combined heat and moisture movement model. The balance equations of moisture and heat are shown as follow, respectively:

$$\rho_{lw} \frac{\partial \phi}{\partial \mu} \frac{\partial \mu}{\partial t} = \nabla \lambda'_g \nabla (\mu_w + F) + \nabla \lambda'_l \nabla (\mu + F) \quad (4)$$

$$C \rho \frac{\partial T}{\partial t} + (c_{lw} j_{lw}) \nabla T = \nabla \lambda \nabla T + r_v \nabla \lambda'_g \nabla (\mu_w + F) \quad (5)$$

Figure 5: Calculation model floor plan:
(a) second floor and (b) first floor.

Figure 6: Elevation of housing model:
(a) west side and (b) south side.

where C and ρ are specific heat and specific weight of material containing water; c_{lw} , ρ_{lw} and j_{lw} are specific heat, specific weight and flux of liquid phase water; λ is thermal conductivity; λ'_g and λ'_l are gaseous and liquid phase water conductivity for μ_w and μ gradients; r_v is heat of sorption (latent heat of evaporation).

The air conditioning loads of conventional air conditioning and this air circulation system were compared in two rooms of the second floor. Figure 7 shows the target areas of the calculation, table 3 shows the calculation conditions. Figure 8 shows the climate information of the cities. The calculation model is assumed to be unoccupied condition, thus there is no internal heat and moisture and only thermal load due to outside air is considered.

Table 1: Composition of roof and wall.

Roof	Exterior wall
Galvalume	Sidings
Structural plywood	Ventilation layer
Ventilation layer	Moisture-permeable and waterproof sheet
Structural plywood	Structural plywood
Moisture-permeable and airtight sheets	Moisture-permeable sheet
Cellulose fiber insulation	Cellulose fiber insulation
Moisture-permeable sheet	Moisture-permeable sheet
	Plaster board
	Vinyl cloth

Table 2: Physical properties of fibrous insulation (Cellulose fiber insulation) for calculation

Thermal insulation [m]	0.185
Thermal conductivity [W/(m·K)]	0.039
Specific heat [J/(kg·K)]	1880.0
Specific weight [kg/m ³]	35.0
Moisture conductivity [kg/(m·s·Pa)]	1.550e-10
Moisture capacity [m ³ /(m ³ (kJ/kg))]	3.219e-05

Table 3: Calculation conditions

Item	Parameter
Flow velocity in ventilation layer	0.06 m/s, 0.12 m/s
Calculation conditions	
Circulation route	Summer
	Indoor → Roof ventilation layer → Outside (above 30°C) Indoor → Roof ventilation layer → Indoor (below 26°C)
	Winter
	Indoor → Roof ventilation layer → Indoor (above 25°C)
Indoor temperature	Summer/Winter
Indoor humidity	Summer/Winter
Calculation period	Summer/Winter
Calculation interval	60 s
Weather data	Expanded AMeDAS Weather Data

Area classification		Calculation area
1		Kushiro
2		Hakodate
3		Ueda
4		Kesennuma
5		Sagami-hara
6		Fuchu
7		Fukuoka

Figure 7: Area classification in "Residential building energy standard" and calculation area.

(http://www.ibec.or.jp/ee_standard/build_standard.html, Institute for Building Environment and Energy)

Figure 8: Annual average temperature and precipitation of target areas for simulation (Climate-Data.org).

Previous studies (Lee and Ozaki, 2018) have shown that the dehumidification effect increases with increasing air flow rate through the roof ventilation layer. However, considering the exhaust-only ventilation system, if the amount of air exhaust increases, the amount of ventilation introduced into the room from the outside is increased, thereby increasing the thermal load from the outside air. According to the standard for 0.5 air-change per hour, the air velocity of the exhaust air through the roof ventilation layer in the proposed model should be controlled to not exceed 0.16 m/s. Therefore, at first, the dehumidifying effect was confirmed under the conditions of 0.06 m/s and 0.12 m/s. Therefore, at first, the dehumidifying effect was confirmed under the conditions of 0.06 m/s and 0.12 m/s as the condition below.

Dehumidification and heat dissipation in summer and solar heat collection in winter

Figure 9 shows the temporal changes as an example of the results when the cooling temperature was set at 27°C and the relative humidity in natural condition. In summer, air circulation to the roof ventilation layer reduced the relative humidity in the LDK (Living room and Dining Kitchen) 10% to 15% compared to the conventional air conditioning. The dehumidification effect all day long can be confirmed by the passive dehumidification due to the exhaust of moisture transferred through the fibrous insulation by solar radiation heat during the daytime and the dehumidification by moisture adsorption into the fibrous insulation at nighttime. Figures 10 shows the temporal change of temperature and humidity in ventilation layer based on the calculation conditions. As the air velocity is increased, the ventilation and humidity layer temperature is decreased during daytime because the heat and moisture in the ventilation layer is exhausted. At night, the lower the flow velocity, the better the dehumidification effect by moisture adsorption. However, it is necessary to consider the cooling effect by radiative cooling, which improved as flow rate increase. In this paper, the temporal changes by numerical simulation are expressed. However, the fibrous insulation material with a high moisture capacity particularly in the actual phenomenon has an unsteady physical property which greatly changes depending on the range of the humidity change. Therefore, there is a limit to the detailed analysis of the phenomena inside the roof, especially fibrous material, through the steady physical properties. Therefore, it is planned to investigate the change of temperature and humidity by this system more closely through comparison with measured values obtained from experiments conducted in actual houses and numerical simulation using unsteady physical properties. Figure 11 and 12 show the effect of latent and sensible heat load reduction in summer respectively. Figure 13 shows the effect of sensible heat load reduction in winter. In the area where the latent heat load occurs (excluding one area), the latent heat load reduction was 80–95% in the house model that uses the system. The sensible heat load reduction effect was 4–10% during the summer. In winter, the sensible heat load decreased 22–28% in all areas. The

sensible heat load effect by radiant cooling was relatively not significant compared to winter. It was considered because the temperature change due to radiative cooling was smaller than the temperature change due to solar heat and due to the high heat storage of the insulating material. To enhance the effect, further research is needed on the set temperature as a reference for fan unit operation and the air flow rate through the roof ventilation layer.

Conclusion

This study proposes an intelligent skin system for a detached house able of dehumidification in summer and solar heat collection in winter using air circulation in the roof ventilation layer and solar energy. Based on our previous research results and supported by theory and basic laboratory experiments, a single house with a passive conditioning system was designed. The thermal load reduction effect of system operation in the model house was simulated. Compared to the conventional room air conditioning, the latent heat load was reduced 80–95% and the sensible heat load was reduced 4–10% in summer, while sensible heat load was reduced 22–28% in winter.

We currently build detached houses based on this research. To investigate the actual application and optimization of this system for real houses, measurements and analysis of the temperature, humidity, and power consumption of the houses are in progress. Therefore, the effectiveness of the proposed system is under verification through comparative experiments. Moreover, in order to optimize its effectiveness, the temperature setting as a reference for operation and the flow rate of the air circulation in the roof ventilation layer is being studied. In addition, further studies are under consideration to take into account the occurrence of internal humidity caused by human activities in the residence.

Figure 9: Comparison indoor humidity change in 2F LDK during summer (Fukuoka, flow velocity: 0.12m/s).

(a) Temperature in ventilation layer

(b) Relative humidity in ventilation layer

(c) Absolute humidity in ventilation layer

Figure 10: Tempal changes of ventilation layer temperature and humidity (Area 7: Fukuoka).

Figure 11: Latent heat load reduction during summer.

Figure 12: Sensible heat load reduction effect during summer.

Figure 13: Sensible heat load reduction during winter.

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