Performance Evaluation of Passive Hygrothermal Control for Houses using a Thermodynamic HAM Model

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Abstract
An intelligent housing envelope system that was capable of passive dehumidification and radiative cooling in summer, solar heat collection, and humidity control in winter, was developed (PDSC system: Passive dehumidification and solar collection system). In this study, a numerical simulation using a thermodynamic HAM (Heat, Air, and Moisture) model was performed to reproduce a house to which the PDSC system was applied, and the performance of the system was investigated. The changes in temperature, relative humidity, absolute humidity, and heat loads, depending on the different envelope compositions, such as a non-permeable envelope, a moisture-permeable envelope (high moisture capacity and low moisture capacity), and the PDSC system were compared and examined. The humidity control ability of the moisture-permeable envelope with high moisture capacity and excellent dehumidification performance of the PDSC system were confirmed.

Key Innovations
• Passive dehumidification and radiative cooling effects were confirmed by performing numerical simulations based on field measurements comparing different envelope compositions.
• A passive dehumidification system was evaluated by numerical simulation using a detailed numerical model with the thermodynamic HAM model.

Practical Implications
A simulation using a detailed numerical model of the combined heat, moisture, and air transfer using the chemical potential reproduced the proposed system, and a performance evaluation was performed. This verified the accuracy of the simulation and reviewed the excellent effects of the PDSC system by comparing different envelope compositions.

Introduction
Conventional air-functioning, cooling, and dehumidification by water vapor condensation in hot and humid seasons (summer season in Japan) are required for a comfortable and healthy environment. However, recent air conditioners, developed with exceptionally high efficiency, maintain a high refrigerant temperature during cooling compared to conventional air conditioners. Although the energy consumption is reduced because of the system, the dehumidifying capacity of the air conditioner becomes weak. Moreover, air conditioning equipment with dehumidification requires high initial and ongoing running costs, and there is no effective passive method for latent heat load reduction during cooling in summer. Therefore, an innovative passive system that is capable of controlling the latent heat load is required for future zero-energy houses.

In our previous research, the basic principles of the intelligent passive dehumidification and solar collection (PDSC) envelope system were outlined using thermodynamic potential theory (Lee et al, 2017). Moreover, the PDSC system effects (passive dehumidification and radiative cooling during summer and solar collection and humidity control during winter) and parameters affecting the effects were examined by model experiments in an environmental laboratory and with numerical simulation (Lee et al, 2019). Furthermore, an actual house with this system was designed and constructed, and its applicability to the actual living environment was verified (Lee et al, 2020).

In this study, we aimed to evaluate the passive dehumidification performance of the PDSC system with numerical simulation using a thermodynamic HAM model and the results obtained from field measurements of actual houses. The effects were examined by comparing the results of two houses, one with the PDSC system and the other without, that had been built side by side on the same parcel, with identical envelope composition and specifications. A numerical analysis was performed to examine the differences in temperature, humidity, and heat load according to different envelope specifications and compositions, such as the moisture capacity of the thermal insulation material or impermeability, while considering various weather conditions.

Numerical Simulation using Thermodynamic HAM Model for Hygrothermal Environment Analysis
The passive dehumidification performance of the PDSC system was evaluated using the building temperature, humidity, and heat load prediction software THERB for HAM’. P-model is adopted as a calculation model of
THERB for HAM (Ozaki et al. 2005). It enables detailed and accurate prediction of moisture transfer including moisture adsorption and desorption of the wall using thermodynamic energy. Figure 1 demonstrates the heat and moisture transfers of the P- model.

\[ \mu_w + \frac{\partial \mu_w}{\partial x} dx + \frac{\partial \phi}{\partial t} + c_{lw} j_w \nabla T = \nabla \lambda \nabla T + r_v \nabla \lambda'_g (\mu_w + \mu_f) \] (1)

where \( \mu_w \) is the specific humidity, \( c_{lw} \) and \( j_w \) are the specific heat and air flow of the material containing water, respectively; \( \lambda \) is the thermal conductivity; \( \lambda'_g \) and \( \lambda'_s \) are the gaseous and liquid phase water conductivities for \( \mu_w \) and \( \mu_f \) gradients, respectively; and \( r_v \) is the heat of sorption (latent heat of evaporation).

Balance equations of heat and moisture transfer in material were obtained as follows:

\[ \rho \frac{\partial \phi}{\partial t} + \frac{\partial \phi}{\partial t} = \nabla \lambda'_s (\mu_w + \mu_f) + \nabla \lambda'_g (\mu + \mu_f) \] (2)

• Heat Balance

\[ \frac{\partial \phi}{\partial t} = \nabla \lambda'_s (\mu_w + \mu_f) + \nabla \lambda'_g (\mu + \mu_f) \] (3)

• Moisture Balance

where \( C \) and \( \rho \) are the specific heat and density of the material containing water, respectively; \( c_{lw} \) and \( j_w \) are the specific heat and flux of liquid phase water, respectively; \( \lambda \) is the thermal conductivity; \( \lambda'_g \) and \( \lambda'_s \) are the gaseous and liquid phase water conductivities for \( \mu_w \) and \( \mu_f \) gradients, respectively; and \( r_v \) is the heat of sorption (latent heat of evaporation).

Water potential, \( \mu_w \), which is derived by applying the chemical potential of thermodynamics to moisture diffusion, is used as the driving force of moisture transfer (Ozaki et al. 2001). The water potential, \( \mu_w \), at a certain temperature \( T \) and water vapor pressure, \( p_w \), can be expressed as the sum of the saturated water potential, \( \mu_w^0 \), and unsaturated water potential, \( \mu \), as follows:

\[ \mu_w(p,T) = \mu_w^0(T) + \mu(p,T) \] (5)

The saturated water potential is the thermodynamic energy of saturated humid air at a given temperature and can be expressed as follows:

\[ \mu_w^0(T) = 6.44243 \times 10^5 + c_{p,\text{wkg}}(T - 273.15) \]

\[ -T c_{p,\text{wkg}} \ln \frac{T}{273.15} + T R_{\text{wkg}} \ln \frac{p_w}{p_s} \]

\[ \mu(p,T) = \frac{\partial \mu_w}{\partial p_w} \] (6)

where \( p_s \) is the saturated vapor pressure at temperature \( T \) and \( c_{p,\text{wkg}} \) is the specific heat expressed in J/(kg·K).

The unsaturated water potential is the negative energy indicating the degree of drying from the saturated state and can be expressed as follows:

\[ \mu(p,T) = R_{\text{wkg}} T \ln \frac{p_w}{p_s} \]

where \( p_w \) is the humid-air vapor pressure and \( R_{\text{wkg}} = 461.50 \) J/(kg·K), as determined by dividing the gas constant, \( R = 8.31441 \) J/(mol·K), by the molecular weight of water, 18.016x10⁻³ kg/mol.

The force potential resulting from the state of internal energy and applied external forces is represented by \( \mu_f \).

For example, when calculating the force potential of water, including the influences of gravity and internal pressure, the equation is represented as follows:

\[ \mu_f = g z + p\bar{V}_w \]

where \( g \) is the acceleration due to gravity, \( z \) is the height of the subject water from the reference position, \( \bar{V}_w \) is the volume per unit weight of water, and \( p\bar{V}_w \) is equal to \( R_{\text{wkg}} T \).

Passive Dehumidification of PDSC System

To enable further understanding of this study, the concept of passive dehumidification of the PDSC system is briefly described in Lee et al. (2019). This system functions as passive dehumidification and radiation cooling through the summer mode operation. The basic envelope configuration is a moisture-permeable envelope with a thermal insulation material of high moisture capacity and a ventilation layer on the outside of the insulation material. The roof is favorable for solar heat gain, and therefore, this system was installed on the roof and investigated. When the temperature of the roof ventilation layer increases above the indoor temperature due to solar radiation, indoor air is circulated to the roof ventilation layer and is discharged outdoors. When the temperature of the roof ventilation layer increases, moisture from the insulation material is desorbed to the roof ventilation layer, and the absolute humidity of the roof ventilation layer and the indoor space become almost the same. This is because of forced air circulation using a fan; however, the difference in water potential occurs, allowing indoor moisture to permeate the ventilation layer. By discharging this moisture to the outside through air circulation, the daytime dehumidification effect was obtained (Figure 2).
cycle, the dehumidification effect was obtained throughout the day.

Figure 2: Passive daytime dehumidification concept.

**Numerical Analysis Subject: Detached House Incorporated with PDSC System**

A house with the PDSC system installed was designed, and field measurements were performed (Lee et al., 2020). The effects of passive dehumidification and radiation cooling in summer and solar collection and humidity control in winter in the house were verified. Using the demonstration house as the subject of the simulation analysis, this study examined the changes in temperature and humidity, heat load reduction according to the presence or absence of moisture adsorption and desorption, and locality (weather conditions). To understand the simulation target, an overview of the demonstration house and the measured results of the passive dehumidification effect are briefly described in this section.

Figure 3 presents the exterior of the two demonstration houses, that are two-story wooden houses, in Itoshima City, Fukuoka Prefecture, Japan. One is incorporated with the PDSC envelope system (hereinafter, Building A), and the other is a conventional house (hereinafter, Building B). To measure the temperature and relative humidity of the indoor room and roof ventilation for both the buildings and the outdoor air, temperature and humidity sensors were implemented. Figure 4 demonstrates the roof composition of the two demonstration houses. When air was circulated using the roof ventilation layer in Building A, indoor air was drawn into this layer by a forced fan. The roof ventilation layer of Building B was designed to permit outdoor air to pass through. The effects of this system were verified by comparing the houses. Both houses were designed and constructed with similar structure and specifications, with the exception of the air circulation system that used a roof ventilation layer.

The thermal insulation material of the east and west surfaces was improved to suppress the difference in temperature and humidity fluctuations between the two buildings because of the influence of solar radiation.

Figure 3: Demonstration houses.

![Demonstration houses.](image)

Figures 5 and 6 show the distribution and the time cumulative graph of relative humidity (1% intervals) and absolute humidity (0.1 g/kg intervals) in living, dining, kitchen (LDK) areas from July 1–28, 2019. The cumulative graph indicates the ratio of the data when the relative humidity value was higher than the relative humidity corresponding to the x-axis within the period. The distribution graph indicates that the distribution of humidity in Building A was lower than in Building B.
Numerical Analysis of Dehumidification and Humidity Control Performance

To accurately compare the performance of the building envelopes with moisture adsorption and desorption, a numerical analysis was performed using THERB for HAM.

Simulation contents and verification of simulation accuracy

The dehumidification effect of the PDSC system was verified by comparing the houses with, and without, the PDSC system. Although Building B is considered to be a conventional house, it has a moisture buffer effect because its structure is a moisture-permeable envelope equipped with cellulose fiber insulation, exhibiting high water capacity and a ventilation layer on the outside of the insulation material. Therefore, the dehumidification and humidity control performance of this roof and wall composition is superior to that of a conventional house using a high performance heat insulation material with a low water capacity, such as glass fiber insulation (GFI) or vapor barrier. Notably, Japanese energy-saving standards recommend that a vapor barrier be provided to prevent condensation. In this section, the change in temperature and humidity according to the difference in the installation of this system, difference in moisture capacity of the thermal insulation, and difference in the mode adsorption and desorption performances are investigated through numerical simulations.

Table 1 summarizes the composition of the simulation models. The simulation model of Building A, which has a PDSC system, is denoted as Type A (Figure 7(a)) and that of Building B is denoted as Type B (Figure 7(b)). Type C is similar to Type B, except that GFI replaces the cellulose fiber insulation (CFI) as thermal insulation (Figure 7(c)). In Type D, a vapor barrier is installed on the inside surface of the roof and external wall, which is the general method for preventing moisture damage such as condensation (Figure 7(d)). Figure 8 shows the measured values (Buildings A and B) and simulated values (Types A and B) of the LDK from July 3–13, 2019. The simulated temperature and humidity results corresponded well with the measurements and verified the validity of the numerical simulation. It is thought that higher accuracy can be expected if the hysteresis phenomenon of the materials related to moisture adsorption and desorption is considered.

Table 1: Example of a table.

<table>
<thead>
<tr>
<th>Classification</th>
<th>Composition of simulation models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A</td>
<td>Simulation model of Building A (incorporated with PDSC system)</td>
</tr>
<tr>
<td>Type B</td>
<td>Simulation model of Building B (equipped with CFI)</td>
</tr>
<tr>
<td>Type C</td>
<td>Obtained by replacing the cellulose fiber in Type B with glass fiber insulation (GFI)</td>
</tr>
<tr>
<td>Type D</td>
<td>Obtained by installing a vapor barrier on the inside surface of the building envelope of Type C.</td>
</tr>
</tbody>
</table>
Figure 8: Verification of accuracy by comparing measured values and simulation values of Buildings A and B (July 3–13, 2019): (a) temperature (mean error is about 1.2%), (b) relative humidity (mean error is about 1.5%), and (c) absolute humidity (mean error is about 2%).

Simulation results
The simulated values of temperature, humidity, and absolute humidity of LDK for Types A, B, C, and D are shown in Figure 9 (hereinafter, the temperature and humidity of each type denote those of LDK). The water capacity of the insulation is marginal, and therefore, the relative humidity of Type C is more sensitive to the variation in the relative humidity of the outdoor air than Type B. Type D is more sensitive than Type C. The absolute humidity of Type D is very similar to that of outdoor air. This is because of the absence of moisture adsorption and desorption between the building envelopes and indoor spaces when the outdoor air that enters the room by ventilation is the only moisture source. The difference in the absolute humidity of the outdoor air is in the order of Type D > Type C > Type B. Therefore, the humidity control effect of the moisture adsorption and desorption of the fibrous insulation material with a large moisture capacity was verified. Type A displays lower relative humidity and absolute humidity than Type B because of the air circulation of the PDSC system.

Figure 7: Roof composition of simulation model.
verified the remarkable dehumidification ability of the PDSC system, as well as the humidity control ability of the fibrous insulation with a large water capacity. The difference in humidity is particularly large for rainy or cloudy days with extremely high humidity, such as on July 3. Evidently, when dried by moisture desorption during a sunny day, the fibrous insulation substantially affects the humidity control and dehumidification by adsorbing a large amount of moisture during periods of exceptionally high humidity.

A simulation using meteorological data (standard year, 2001–2010) of the Automated Meteorological Data Acquisition System (AMeDAS, Japan Meteorological Agency) was conducted in July to compare the standard performances of all the types. Figure 10 shows the temporal variations in the simulation results. The relative humidity distribution (5% interval) and cumulative rate graph of the distribution in July are shown in Figure 11. Moisture is adsorbed and desorbed between the envelopes and room in Type C, and therefore, the relative humidity (x-axis) variation width is smaller than that of Type D. Types A and B display distributions between 45% and 75% relative humidity on the x-axis. The variation in relative humidity is significantly smaller. In addition, Type A displays the highest distribution of 50%–60%. Evidently, comfortable indoor humidity is maintained. In the time accumulation rate graph (Figure 11 (b)), the cumulative rate, with a relative humidity of 60% or higher, is approximately 40% for Type A, whereas it is 60% or higher for Types B, C, and D. Evidently, most relative humidity is more than 60% during this period. Type D does not adsorb or desorb moisture and is substantially affected by the humidity of the outdoor air. Therefore, the comfort range of the relative humidity value is distributed at a low rate, and the highest relative humidity distribution is displayed at a very high rate compared to the other types.

Figure 12 shows the distribution of absolute humidity (0.5 g/kg intervals) and the time cumulative rate. There is no moisture adsorption or desorption between the envelopes of Type D and the room, and therefore, the distribution of the Type D absolute humidity is similar to that of the outdoor air. Types B and C release moisture when the relative humidity of the outdoor air is low, and therefore, the absolute humidity may be higher than that of Type D. Type B, which has a large moisture capacity, adjusts the relative humidity by the adsorption and desorption of a large amount of moisture, and therefore, the fluctuation range of its absolute humidity is larger than those of Types C and D. Type A exhibits the lowest absolute humidity distribution because of the dehumidifying function of the PDSC system, and it can be verified that the low humidity is maintained by the remarkable dehumidification function achieved by installing the PDSC system.

**Figure 9:** Comparison between Types A, B, C, and D (July 3–13, 2019): (a) temperature, (b) relative humidity, and (c) absolute humidity.

**Figure 10:** Comparison of Types A, B, C, and D (July): (a) temperature, (b) relative humidity, and (c) absolute humidity.
Comparison of Cooling Load Variation According to External Weather Conditions

Simulation conditions and target regions
The differences in heat loads of the simulation models with respect to the external weather conditions during cooling were compared. Figure 13 shows the target areas used for the investigation. The target area was selected based on the regional classification of Japan’s energy-saving standards, for example, area classification by municipality name, and annual solar heat area classification (General Association of Housing Performance Evaluation and Labeling, October 2015). The meteorological data used were from the standard year of the AMeDAS weather data. The results from August 1–31 were analyzed. The room cooling conditions were temperature = 28 °C and relative humidity = 60%.

Simulation results
Figure 14 indicates the sensible and latent heat loads of the entire house according to the types in each region. Figures 15 indicates the variations over time in the temperature, relative humidity, and absolute humidity of Fukuoka.
when examining the variation over time, the relative humidity and absolute humidity were in the order of Type D > Type C > Type B. The lower the water capacity, the more sensitive the indoor humidity to variations in temperature and humidity. Therefore, when the air conditioner is mainly operated during the daytime, the latent heat load of the type with a small water capacity may decrease marginally; however, the humidity increases substantially during the nighttime when the air conditioner is not operated. The results of this simulation validate the humidity control performance of the insulation material with a large water capacity and the dehumidification effect of the PDSC system in most regions except the northern region, where the cooling load was highly marginal. When considering the indoor heat and moisture generation as well as the external air load, because the operation time of the air conditioner is longer, a higher humidity control and dehumidification effect can be predicted. This investigation will be discussed in a subsequent report.

**Figure 14: Comparison of heat load depending on weather condition.**

<table>
<thead>
<tr>
<th>Type</th>
<th>Sensible</th>
<th>Latent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type A</td>
<td></td>
<td></td>
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<tr>
<td>Type B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type D</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 15: Temporal change of Fukuoka.**

(a) temperature, (b) relative humidity, (c) absolute humidity

**Conclusion**

Numerical simulations were performed to analyze the variations in temperature and humidity and the difference in load reduction effects, depending on different envelope compositions and weather conditions.

Two demonstration houses were used to examine four types of envelope compositions to analyze the effect of humidity control and cooling load reduction in summer (Type A: house with PDSC system, Type B: house of moisture-permeable envelope with CFI, Type C: with GFI rather than CFI, Type D: with vapor barrier). The results reveal that the indoor relative humidity of the envelop with vapor barrier fluctuates severely due to changes in the external humidity. However, the indoor with high water capacity and hygroscopic envelopes show more gentle relative humidity changes. Moreover, the PDSC system can be used to obtain the significant effect of latent heat load reduction with sensible heat load reduction. The effect of 20%–40% reduction in the latent heat load by the PDSC system was verified in all areas except the northern area, which incurs low cooling loads.

**Acknowledgement**

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**References**


Lee, H. and A. Ozaki (2020), Housing design methodology for passive hygrothermal control and effect verification via field measurements. *Building and Environment* 185, 1072