A Systematic Parametric Study on a Passive Room- Dehumidifying System Using the Sorption Property of a Wooden Attic Space

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ABSTRACT: In hot and humid tropical regions, challenge of air dehumidification has increasingly been regarded as one of the important issues in preventing high moisture-related problems. In relation to this, the desiccant dehumidification system has recently been of great interest, especially passive systems. With respect to this issue, the passive room dehumidifying system using the sorption property of a wooden attic space was proposed, with its merits of low initial cost and non-degradable desiccant material use. This study aims to describe the effect of each parameter on the system performance, which is calculated by mathematical simulation models, through a factorial design and statistical procedure with respect to parameter variations and their interaction effects. Consequently, the reductions in the air infiltration of bedroom along with a number of occupants corresponding with a certain unit of the system could be considered as the most influential factors to improve the system performance. In addition, a decrease in air infiltration of attic space would increase the system potential as well as the increase in roof area and ventilation between attic and bedroom during the night. Additionally, as expected, it can be considered that the system can perform well under the circumstances with high daily summation of solar radiation.

Keywords: dehumidification, attic, statistical analysis, parametric study

1. INTRODUCTION

In hot and humid tropical regions, air dehumidification is widely regarded as one of the keys to achieving a better indoor environment. Of particular interest are studies on systems using a passive approach. While usual systems require high capital investments and use degradable chemical desiccants, this study emphasizes on a passive room-dehumidifying system using the sorption property of a wooden attic space with benefits of low initial cost and non-degradable desiccant. Although the feasibility of the system has been carried out [1], due to the complicacy of the system, a parametric study is, therefore, considered to be necessary.

2. CONCEPT OF THE SYSTEM

In Fig.1, the operation of the system during the day and night is illustrated. An airtight wooden attic space plays a role as the chamber, while the plywood beneath roof components works as the desiccant material. During the day, the high temperature in the attic space regenerates the plywood and moist air is vented to the outside by exhaust ventilation. Inversely, at night, the plywood absorbs moisture from humid air supplied from the bedroom with the presence of occupants generating both moisture and sensible heat load. After the air is dried by the absorption process of the plywood, it is subsequently fed back into the bedroom. In addition, the sensible heat load generated by the occupants and the absorption process taken place in the plywood is dissipated through the roof components, which are subject to nocturnal radiation. This cycle is repeated throughout the night. The decrease in air humidity of the bedroom during the night due to the moisture absorption of the attic space is considered to be the extent of the dehumidification.

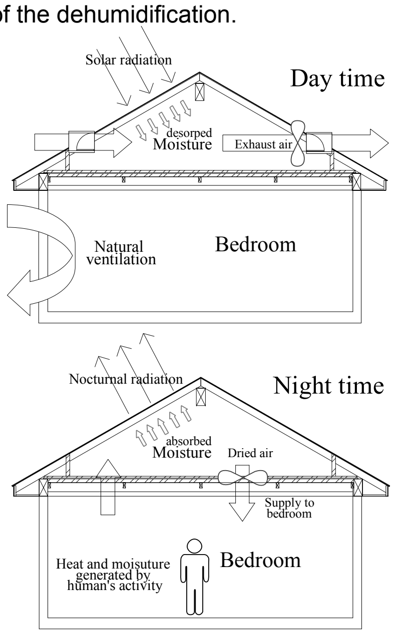

Figure 1: Schematic view of the operation of the system during the day and night.

3. NUMERICAL CALCULATION MODELS

The calculation software used in this study is a one dimensional hygrothermal simulation program called H-AIR, first developed by Sakamoto based on the mathematical models of Matsumoto [2]. It is particularly designed to perform a calculation of multiple-room conditions with extension of the sorption mechanism of building envelopes using temperature and absolute humidity as driving potentials with accuracy particularly within the hygroscopic region (0% - 95% of relative humidity). In this region, the predominant moisture transport mechanism is considered to be mainly vapour diffusion, as liquid transport is comparably negligible.

The main mathematical models are classified according to their functions into four groups. The governing equations for building envelopes (1,2) and for boundary conditions (3,4) are dealing with thermal and moisture behaviour of building's envelope, while the budget equations of a room plays a part in indoor air condition's calculation as shown in (5,6).

$$\left(\frac{c\rho k}{c\rho + rv}\right)\frac{\partial X}{\partial t} = \frac{\partial}{\partial x}\left(\lambda'\frac{\partial X}{\partial x}\right) + \frac{\partial}{\partial x}\left(\frac{v}{c\rho + rv}\lambda\frac{\partial T}{\partial x}\right) \quad (1)$$

$$c\rho\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial x}\left(r\lambda'\frac{\partial T}{\partial x}\right) \quad (2)$$

$$\left[-\lambda\frac{\partial T}{\partial x}\right]_s = \alpha(T_o - T_s) \quad (3)$$

$$\left[-\lambda'\frac{\partial X}{\partial x}\right]_s = \alpha'(X_o - X_s) \quad (4)$$

$$\Gamma\frac{dX_r}{dt} = W_t + \rho_w G(X_o - X_r) + \sum_{i=1}^{N}\alpha'_i S_i\left(X_{s_i} - X_r\right) \quad (5)$$

$$c\Gamma\frac{dT_r}{dt} = H_t + c\rho_a G(T_o - T_r) + \sum_{i=1}^{N}\alpha_i S_i\left(T_{s_i} - T_r\right) \quad (6)$$

$$k = \rho_w\sigma\frac{\partial h}{\partial X} \qquad v = -\rho_w\sigma\frac{\partial h}{\partial T}$$

where,

T : temperature (^oC)
X : absolute humidity (kg/kg DA)
x : thickness (m)
λ : thermal conductivity (kcal/m hK)
λ' : vapour permeability (kg/m h(kg/kg DA)
r : latent heat of evaporation (kcal/kg)
c : specific heat (kcal/kg K)
ρ : density (kg/m^3)
α : surface heat transfer coefficient ($kcal/m^2hK$)
α' : surface moisture transfer coefficient (kg/m^2 h(kg/kg DA)
Γ : dry air weight of room volume (kg)
G : Ventilation rate (m^3/h)
W : moisture generation (kg/h)
H : heat generation (kcal/h)
S_i : surface area of i wall (m^2)
N : number of walls
h : relative humidity (ratio)
σ : slope of the equilibrium moisture content (-)

subscript:

a : air
w : water
s : surface
o : outdoor
r : room

4. BUILDING MODEL DESCRIPTION

The typical wooden residential building in Japan for a family with 4 members, plans and elevations drawing, which are shown in Fig.2, is applied as a standard model for performing simulation. Here, the focuses of attention are the attic space and bedrooms on the second floor. In the calculation process, in order to simplify the calculation conditions, firstly, the heat and moisture transfer of the attic space and bedroom with other parts of the building are completely neglected and secondly, 3 bedrooms are combined into a single space with 4 occupants. Additionally, the characteristics of the attic space and combined single bedroom space are illustrated in Table 1.

The roof components consist of colonial concrete asphalt roof, asphalt sheet, plywood and wood rafter respectively from outside in. The floor of the attic space is greatly insulated by a total of 130mm polyethylene insulation to minimize heat flow into the 2nd floor. The typical wall consists of a siding wall, air space and plywood sheet.

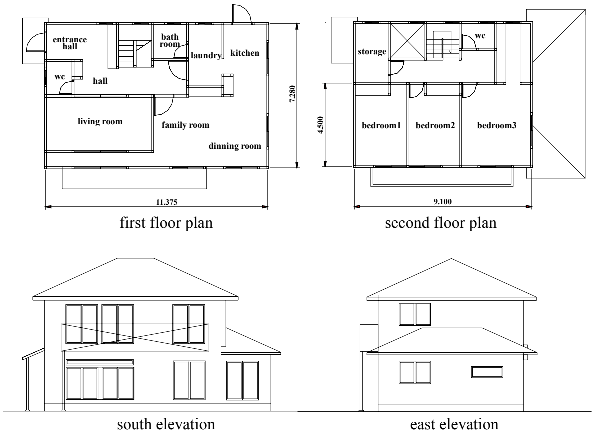

Figure 2: Plans and elevations of the building model for the simulation.

Table 1: Characteristic of the attic space of the typical wooden Japanese house used as model in this study

Characteristic	Attic	Bedroom	Unit
Floor area	65.85	40.95	m^2
Room volume	33.60	98.28	m^3
Air infiltration rate	0.50	0.50	time/h
Surface area of free floating wooden components	16.40	20.43	m^2
Daytime exhaust Ventilation rate	12.00	-	time/h
Nighttime ventilation between attic & bedroom	-	4.00	time/h
Thickness of the plywood beneath roof	12.00	-	mm

5. FACTOR SIMULATION DESIGN

5.1 Factorial design

In experimental or complicated simulation investigation, factorial design is one of the common tools for parametric study, which considers the responses or effects of the system concerning two or more factors. Since there is a possibility that the response of the system at one level of a factor is not maintained constantly while other factors alter, the principles of full factorial experiment design, which all possible combinations of the levels of the factors are investigated, were applied in this study for the twelve-factors simulation design. In addition, the total number of combinations is 69984.

5.2 Factors description

In this study, the dependent variable or response of the system is the dehumidification potential of the system or in other words, the difference in absolute humidity between the bedroom and outdoors. This means that the dehumidification potential is positively high when the level of humidity inside the bedroom is lower than the level outside. Throughout this paper, the term "Dehumidification index" is used instead of this difference.

The independent variables are divided into two groups, fixed and random. The independent fixed variables are internal factors such as ventilation between attic space and bedroom, daytime ventilation of attic space, air infiltration rate in attic space and bedroom, thickness of the plywood beneath the roof, number of occupants, the surface area of the free floating components in attic space (wooden skeleton structure elements) and bedroom (furniture) and roof surface area. The random variables are external factors such as daily temperature, absolute humidity and summation of solar radiation. In term of random variables, the standard weather data of 3 cities for a month during the summer in Japan were used and categorized into low and high by the margin of 28 °C, 18 g/kg DA and 3100 W h/day for daily average outdoor temperature, absolute humidity and daily summation of solar radiation respectively.

5.3 Range of parameters

As illustrated in Table 2, the range of parameters, related to the internal factors concerning the attic space and bedroom and external factors, was designed in order to cover the possible properties of wooden building configurations.

5.4 Statistical analysis

For the purpose of clarifying which parameters are considered as having any practical importance and significant effects over the system performance, the principle of the magnitude of effects is utilized. There are a number of methods of assessing the magnitude of the effects. Among them, Omega-square, which was used throughout this study, is considered as one of the least biased measures. It values each effect according to how much variability can be attributed to the treatment effect in terms of the ratio relative to the total variance. Furthermore, Omega-square also allows us to differentiate between fixed and random variables and act accordingly.

Table 2: Range of the parameters

Factor	Parameters	Level 1	Level 2	Level 3
A	Daily average temperature	Low	High	-
B	Daily average absolute humidity	Low	High	-
C	Daily summation of solar radiation	Low	High	-
D	Ventilation between attic and bedroom (ach)	2.00	7.00	12.00
E	Daytime exhaust ventilation of attic space (ach)	2.00	7.00	12.00
F	Air infiltration of attic space (ach)	0.50	1.25	2.00
G	Air infiltration of bedroom (ach)	0.50	1.25	2.00
H	Thickness of the plywood beneath the roof (mm)	6.00	15.00	24.00
I	A number of occupants (person)	0	2	4
J	Surface area of the free-floating wooden components in attic (m^2/m^2 floor area)	0.00	0.25	-
K	Surface area of the free-floating wooden components in bedroom (m^2/m^2 floor area)	0.00	1.00	-
L	Roof area (ratio to original roof area)	0.80	1.00	1.20

In order to calculate the Omega-Square index, as illustrated in equation (7), the ratio of estimated individual effect variance to total variance is applied.

$$\omega^2 = \frac{\sigma^2_{effect}}{\sigma^2_{total}} \quad (7)$$

In analysis of variance (ANOVA) design, total variance can be achieved by the summation of all possible individual variance components including error variance. In addition, in order to yield the individual effect variance components, the manipulation between the expectation of mean squares or E(MS)s [3] is to be performed. The components of variance in each E(MS) depend to a great extent on whether the model(variables system) are fixed, random or mixed. As the model in this study is mixed, the simplest way to obtain the expectation of mean squares is to firstly write out the expectations of mean square of all sources as if they are random variables. Afterwards, in case that any of them is fixed variable, by considering E(MS)s one by one, certain components of variance of certain E(MS) are then to be deleted. Since there are twelve factors in this study, which make it not practical to express all components of variance here, please refer to the examples of the manipulation of components of variance in [4]. Additionally, in order to be able to substitute the values of E(MS)s, the value of the estimated mean square of each effect and interaction can be achieved by firstly calculating the sum squares [5] and subsequently dividing them with the corresponding degree of freedoms.

Table 3: Evaluation of the magnitude of the effects by Omega-Square

Magnitude of effect	Omega-Square
Small effect	≧0.01
Medium effect	≧0.06
Large effect	≧0.15

Table 4: Distribution of the Omega-Squares regarding to the main factors and interactions.

Factors	Omega-Square	Magnitude of effect
I	0.341	Large
G	0.207	
L	0.128	Medium
F	0.095	
D	0.065	
H	0.037	Small
C	0.015	
I*G	0.013	
F*G	0.010	

To evaluate the significant magnitude of effect, the criteria based on the study by Cohen [6] are applied as illustrated in Table 3. In addition, in order to have a better understanding of how the system is influenced, the relationships between factors involved in the system and the dehumidification potential of the system were analysed through its marginal means.

6. RESULTS AND DISCUSSIONS

6.1 Magnitude of effects

As illustrated in Table 4, the distribution of the Omega-Squares relating to the main factors and interactions are shown. Accordingly, with large effect, there are the number of occupants and the air infiltration of the bedroom as the Omega-Squares are as high as 0.341 and 0.207 respectively. In addition, the factors with medium effect are the roof area, air infiltration of the attic space and ventilation between the attic space and bedroom by the Omega-Squares of 0.128, 0.095 and 0.065 in orders. Besides that, the main factors with small effect are the thickness of the plywood beneath the roof components and daily summation of solar radiation due to its Omega Squares of 0.037 and 0.015 respectively. Moreover, there are the interactions of the air infiltration of the bedroom with the number of occupants and air infiltration of the attic space with small effects as its Omega-Squares are 0.013 and 0.010 accordingly.

Therefore, it can be taken into consideration that a number of occupants corresponding with a certain unit of the system plays the most important role in determining the system potential. Here, it comes as no surprise because a number of occupants represent the source of latent heat generation, which directly affects the potential of the system. Besides a number of occupants, air infiltration in bedroom is the most influential factor on the dehumidification potential of the system due to its Omega-Square concerning both the main effect and interactions with other factors. In addition, with medium and small effects, roof area, air infiltration of attic space, ventilation between attic space and bedroom and thickness of the plywood beneath the roof components are considered as important internal factors. Among external factors, daily summation of solar radiation is also ranked as one with significant small effect.

On the other hand, according to the results, it is almost certain that as long as the level of parameters are maintained in the range of this study, the internal factors such as daytime exhaust ventilation of attic space and surface area of the free-floating wooden components in the attic space and bedroom have negligible effects on the system performance as their Omega-Squares are less than 0.01. Since humidity is extremely sensitive to ventilation, it can be explained regarding to daytime exhaust ventilation of the attic space that by 2 air change rate/hour of the ventilation is sufficient for venting out the released moisture from the plywood. High ventilation rate does not result in higher potential of the system because it lowers the temperature of the plywood and subsequently lessens the potential of the drying process. Additionally, although the sorption mechanism with time of the free-floating wooden components in attic space plays a different role from the plywood beneath the roof components, it does not significantly affect the system potential due to it has small surface area comparing to that of the plywood. Furthermore, since the moisture content of free-floating wooden components in bedroom are maintained at a nearly constant level, unlike that in the attic space where the difference in temperature between day and night are fairly extreme, it reaches the equilibrium state with the surrounding air and barely has sorption potential sufficient to influence the bedroom's humidity.

Regarding the external factors, daily average temperature and absolute humidity are not likely to influence the system performance according to their Omega-Square. It could be due to the fact that the main mechanism of the system is focused on the moisture content of the plywood, which is affected directly by a temperature increase due to solar radiation rather than an air temperature and humidity. Therefore, effects of the temperature and absolute humidity of the air are comparatively small and can be neglected.

6.2 Relationship between factors and effects

Main effects

In Fig.3, the effects of the main factors, in term of dehumidification index, are illustrated. As for the factors with negative effects, as shown in Fig.3 (h), it could be expected that a higher number of occupants in the bedroom corresponding with a certain unit of the system can cause the increase in the generation of the latent heat load, which lowers the potential of the system. Furthermore, it can be estimated from the result that the system can still only dehumidify with maximum occupants of 8 persons under current circumstances. In addition, as shown in Fig.3 (e) and (f), the dehumidification indices are exponentially decayed due to the increase of air infiltration of both attic space and bedroom. It could be explained that due to high humidity level outside at night, higher air infiltration in either bedroom or attic space can cause higher flow in of the moisture.

On the other hand, as for factors with positive effects, the increase in roof area plays an important role in the constant increase of the dehumidification index as shown in Fig.3 (i). As roof area increases, area of the plywood, the main element driving the system, also consequently increases. As a result, the plywood as a whole performs more moisture absorption during the night. Additionally, as can be seen in Fig.3 (c), the ventilation between the attic space and bedroom exponentially increases the dehumidification index and tends to keep it constant after a certain point. Since an increase in the ventilation rate between the attic space and bedroom can induce the bedroom's humidity condition approaching that of the attic space, where absolute humidity is relatively low due to the absorption process, it could consequently help increasing the potential of the system. However, up to a certain point when the humidity of input and output of the ventilation are nearly identical, increase in ventilation rate does not longer increase the potential of the system.

Additionally, as shown in Fig.3 (g), the dehumidification potential reaches the maximum while the thickness of the plywood is approximately 6 mm. It could be explained that despite more thickness of the plywood, which is supposed to produce higher system potential due to the capacity of holding more moisture, during drying process the inner layer of the plywood cannot be properly dried due to its excessive thickness. Thus, the plywood cannot fully operate the

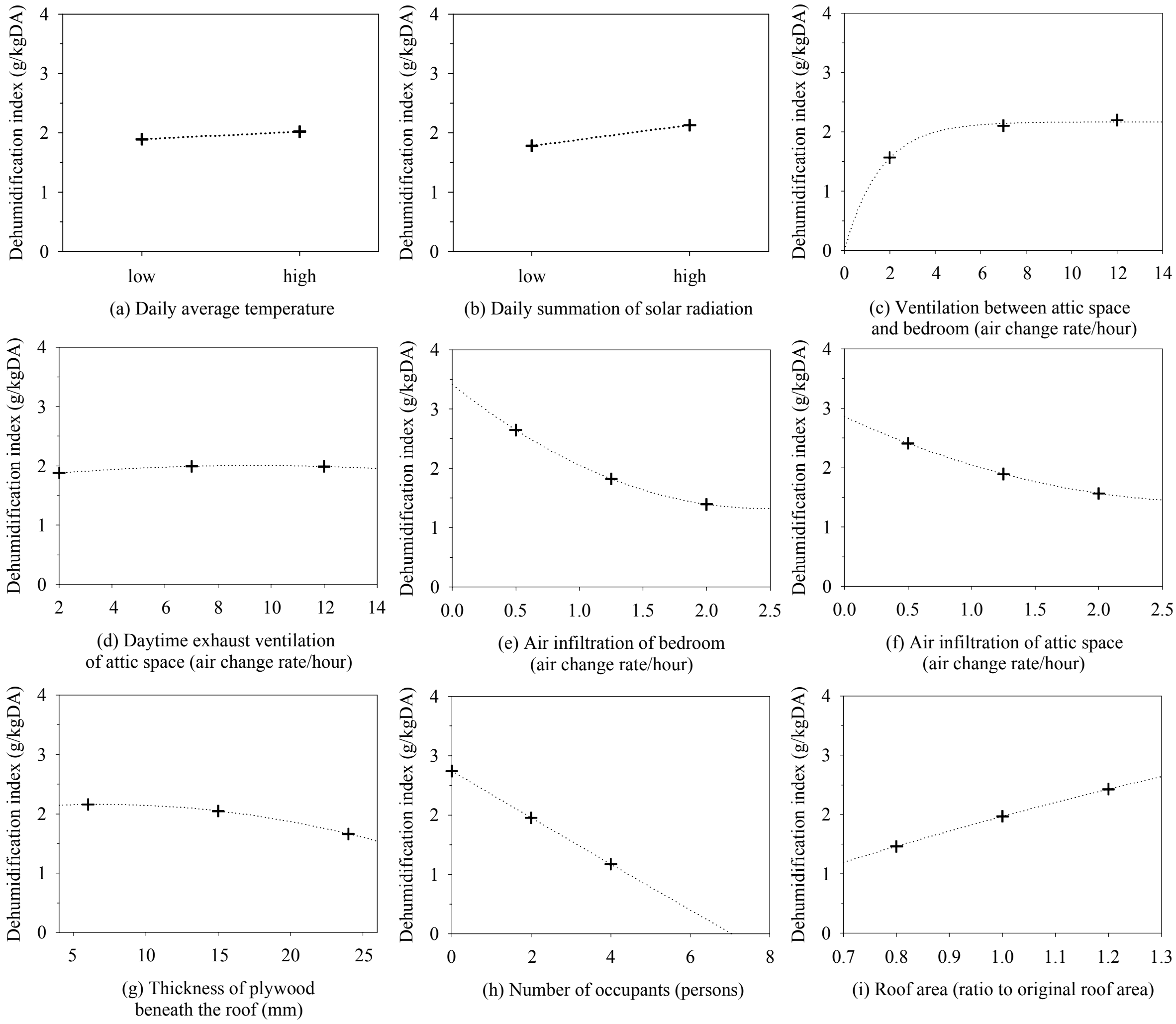

Figure. 3: Effect of the main factors, in term of dehumidification index

absorption process during the night. On the other hand, thin plywood has little capacity to be able to hold the moisture at night.

Furthermore, as illustrated in Fig.3 (b), as expected, it is confirmed that the system can achieve a higher dehumidification index under circumstances of high solar radiation level. As mentioned in the concept of the system that solar radiation plays an important role in drying the plywood underneath the roof during the day. As a result of that, at night, the dried plywood are capable of absorb moisture which in return reduces the humidity in the air.

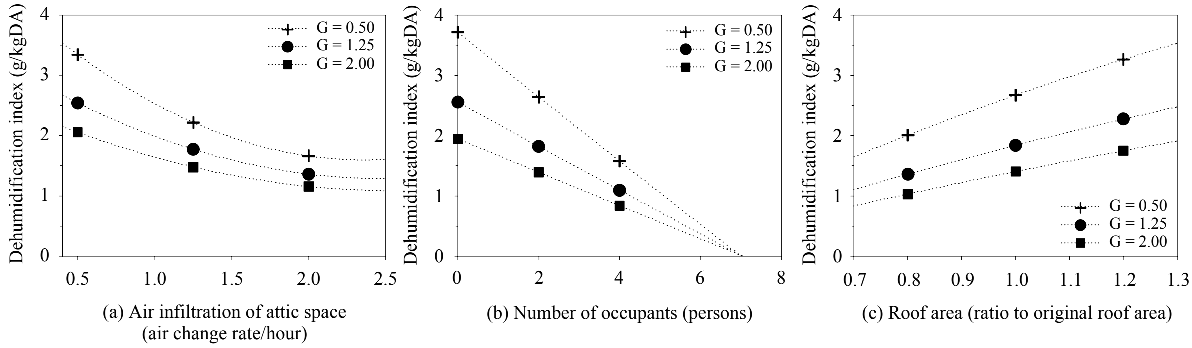

Figure. 4: The effect of interactions, in term of dehumidification index

Interactions

In Fig.4, the effects of the main interactions are illustrated. On the figure, while the air infiltration of the bedroom is as high as 2.00 air change rate per hour, the dehumidification index is significantly low. The change in factors such as, the air infiltration in attic space, the number of occupants and roof area, do not induce the considerable change in the dehumidification index comparing to that of which the air infiltration of bedroom is low. It seems to be the case that for the purpose of maximization of the system performance, the reduction in the air infiltration of bedroom is our first priority. After that, consideration on other factors, are then to be concerned.

7. CONCLUSIONS

This study explores the effects of the parameters involved in this system, on the dehumidification potential of the system through the magnitude and relationship of the effects with parameters.

According to the results concerning internal factors, a reduction in a number of occupants corresponding with a certain unit of the system could be considered as the most influential factor due to its Omega-Square to improve the system potential. Besides that, according to the result of the Omega-Squares of both main effects and its interactions with other factors, a reduction in air infiltration of bedroom also plays an important role in increasing the dehumidification potential. In addition, a decrease in air infiltration of attic space would improve the potential of the system with medium effect. On the other hand, an increase in roof area and ventilation between attic and bedroom during the night could affect the system positively. Thickness of the plywood is considered to provide the higher potential of the system while it is maintained approximately at 6 mm. Among external factors, it can be considered that the system can perform well under the circumstances with high solar radiation level. In addition, it is also illustrated that as long as the parameters, such as daytime exhaust ventilation of attic space, surface area of free-floating wooden components in attic space and bedroom, daily average outdoor temperature and absolute humidity are maintained in the range used in this study, it appears to have negligible effect due to their Omega-Squares

These findings lend support to the conclusion that a development or renovation of the system, such as reduction in air infiltration of bedroom could significantly improve the performance of the system as long as it is higher than the building regulation concerning indoor air quality. Moreover, it leads us to a better understanding of the system mechanism. For future studies, it is also worth mentioning that an experiment with the optimization based on the result of this study and regression model for predicting the system performance before taken into practical process could benefit the purpose of the exploitation and implementation of the system.

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