

Study on Numerical Simulation Applied to Moisture Buffering Design Method – The Case Study of Pine Wood in a Single Zone Residential Unit in Taiwan

Y.C. Yeh, Y.S. Tsay, and C.M. Chiang

Abstract—A good green building design project, designers should consider not only energy consumption, but also healthy and comfortable needs of inhabitants. In recent years, the Taiwan government paid attentions on both carbon reduction and indoor air quality issues, which be presented in the legislation of Building Codes and other regulations. Taiwan located in hot and humid climates, dampness in buildings leads to significant microbial pollution and building damage. This means that the high temperature and humidity present a serious indoor air quality issue. The interactions between vapor transfers and energy fluxes are essential for the whole building Heat Air and Moisture (HAM) response. However, a simulation tool with short calculation time, property accuracy and interface is needed for practical building design processes. In this research, we consider the vapor transfer phenomenon of building materials as well as temperature and humidity and energy consumption in a building space. The simulation bases on the EMPD method, which was performed by EnergyPlus, a simulation tool developed by DOE, to simulate the indoor moisture variation in a one-zone residential unit based on the Effective Moisture Penetration Depth Method, which is more suitable for practical building design processes.

Keywords—Effective Moisture Penetration Depth Method, Moisture Buffering Effect, Interior Material, Green Material, EnergyPlus

I. INTRODUCTION

A good sustainable building design should be considered both the health and comfortableness of the occupants. Recently, Taiwanese government not only promotes the energy efficiency and the carbon elimination projects, but focuses on the Indoor Air Quality issue. In the western countries, there are many researches concerning the effect of humidity on human health. The relative humidity, which is much higher or lower than the average, will cause the illness of the occupants [1], and also the survival rate of air-borne bacteria and viruses decreases when the relative humidity is lower than 40-70% [2], which indicates that the relative humidity causes a direct impact of respiratory diseases and allergies. Also, there is research indicates that indoor environment of a high relative humidity provides a suitable breeding ground for fungi and other microorganisms, especially where children and elderly occupants [3]. Moreover, the high humidity causes also construction problems, such as the decay and ruin of building materials.

Therefore, the humidity issue is one of the essential factors regarding the indoor environment quality. In Japan, the Ministry of Health, Labor and Welfare suggests 40%-70% relative humidity as one of the standards of Indoor Air Quality [4]; the Health Canada suggests 30%-80% relative humidity standard for summer and 30%-55% for winter [5]. Also, the regulation in Singapore is lower than 70% [6]. Taiwan locates in subtropics, which represents a high temperature and high humidity climate phenomenon. According to the data from The Central Weather Bureau of Taiwan, the yearly average relative humidity of the general areas in Taiwan is above 75% and the monthly data is above 70% (1991~2000). Regarding the promotion of sustainability, there is a specific chapter of Green Building regulation in the National Building Code of Taiwan, and also the Taiwan Indoor Air Quality regulation has been proposed and published in 2011. In summer, Taiwan shows higher Indoor concentration of fungi than the U.S. and Finland [7] which shows Taiwan is more suitable for the growth of fungi. The main source of the indoor fungi pollution is from interior materials and air conditioning, especially surfaces of building materials [8]. Therefore, the high temperature and humidity of Taiwan present a serious indoor air quality issue.

In Taiwan, how to apply moisture buffering materials into the indoor environment is being discussed. To evaluate the performance of moisture buffering materials by numerical simulation in terms of health (bio-pollution assessment) and energy consumption (heat load of A/C) is proposed [9]. Also, the location of moisture buffering materials in typical residential is discussed; moisture buffering materials set into double layer wall and raised floor construction combined with ventilation system could help reduce the high humidity [10].

For discussing the influence of building spaces by both Heat and Moisture, the HAM method was proposed. However, most simulation programs present a high accuracy but complicated calculation, which usually takes more time and cost during the process. In this research, the simulation bases on the EMPD (Effective Moisture Penetration Depth) method, also called lumped parameter approach [11] or buffer storage humidity model [12], which is a method assumed that the moisture penetration only happened in a limited depth from the building material surface [13]. In this paper, the EMPD was performed by EnergyPlus, which was developed by DOE (Department of Energy) of the U.S. Therefore, the objectives of this study is to compare the moisture buffering performance of pinewood under different moisture condition setup, to confirm feasibility and practicability that the EnergyPlus applied to moisture buffering simulation of interior materials, and to suggest an ordinary, reliable, and useful simulation tool with accuracy regarding moisture buffering to architecture related industries for supporting building design process. Researchers expect that the results could be developed to the practical reference for architects, interior designers, or other related industries.

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II. METHODS

A. EMPD

EMPD method is a simplified algorithm method to simulate the moisture absorption and desorption of building material surface. This is assumed that the moisture transfer phenomena only could reach a certain depth from the surface in building material, which could be calculated only by the permeability and sorption isotherm. Compared with the HAM model, certain material properties, such as porosity, are not needed in EMPD. Therefore, EMPD could be applied to simulation and reduce the calculating time.

B. Equation

A full calculation of the moisture capacity in an indoor environment is extremely complicated. The detailed information of geometry and heat and moisture material properties will be needed, such as building materials, coatings, furniture, and all the objects which show hygrothermal response. The property information is usually not available or difficult to obtain. Thus, the simplified method to simulate moisture exchange between air and materials could be used to alter.

According to reference [14], equation (1) shows moisture balance for indoor air within a space under the non-steady-state. This balance assumes that the zone air is well-mixed, and all conditions are equal in this zone. The left side of the equation sign presents indoor air moisture capacity along the schedule, which could show the performance of moisture buffering materials; the right side presents all the productions of the moisture, which include the moisture transfer between air and material surface, indoor and outdoor moisture transfer produced by ventilation, humidification or dehumidification of air-conditioning equipment, and moisture internal gain.

$$\frac{V}{R_v T_i} \frac{dP_i}{dt} = \sum_j A_j \alpha_j (P_i - P_{s,j}) + \frac{Q}{R_v T_i} (P_e - P_i) + m_{sys} + m_p \quad (1)$$

Where V means the volume of flow rate of outside air (m^3), R_v is the water vapor constant (462 J/kg/K), T_i means the indoor air temperature (K), P_i presents the water vapor pressure of room i (Pa), t is the time (s), A_j is the area of wall j (m^2), α_j is the surface convection coefficient of wall j (m/s), $P_{s,j}$ presents the surface water vapor pressure of wall j (Pa), Q is the ventilation rate (m^3/s), P_e is the outdoor water vapor pressure (Pa), m_{sys} is the moisture from equipment (kg/s), and m_p is the internal gain of moisture (kg/s)

Equation (2) is one-dimension fundamental HAM model regarding moisture transfer and storage mass balance equation in porous materials. The left side of (2) is the transferring amount of moisture inside the material surface, which is equal to moisture capacity variation of the material. Also, the amount of moisture absorption/desorption inside the material was decided by the RH of porous inside materials.

$$\frac{\partial}{\partial x} \left[\delta(\varphi) \frac{\partial p}{\partial x} \right] = \frac{\partial w}{\partial t} = \rho \xi(\varphi) \frac{\partial}{\partial t} \left[\frac{p}{P_{sat}(T)} \right] \quad (2)$$

Where δ is the vapor permeability (s), φ is the relative humidity, w presents the moisture content by volume (kg/m^3)

$P_{sat}(T)$ is the saturation water vapor pressure at temperature T (Pa), and $\rho \xi$ is the moisture capacity in terms of humidity, derived from the material sorption isotherm (kg/m^3)

Equation (3) is the boundary condition of the interior material surface.

$$\alpha_i (p_i - p_s) = -\delta(\varphi) \frac{\partial p}{\partial x} \Big|_s \quad (3)$$

The basic assumption of EMPD is that under the environmental humidity variation, the hygrothermal interaction only happens in a thin layer of moisture buffering material. This thin layer is called Effective Penetration Depth d_p which is related to the variation of water vapor pressure at the material surface.

The EMPD calculation is (4), which t_p is the period of cyclic variation. For the general porous materials, the unit of the EMPD is mm per day while cm per year.

$$EMPD = \sqrt{\frac{\delta \cdot P_{sat}(T) \cdot t_p}{\rho \cdot \xi \cdot \pi}} \quad (4)$$

$$\frac{P_i - P_b}{\frac{1}{\alpha_i} + Z_b} = \rho \xi(\varphi) \cdot d_p \frac{d}{dt} \left[\frac{P_b}{P_{sat}(T_b)} \right] \quad (5)$$

Where t_p is the period of cyclic variation (s), d_b is the depth of moisture buffering layer (m), Z_b means the vapor diffusion resistance between the surface and the moisture storage center of the layer (s/m), and P_b is the average vapor pressure in the buffering layer (Pa)

Therefore, by the assumption of (4), we could reduce (2) and (3) to (5). As calculating the moisture buffering performance by (5), the indoor P_i and P_b are considered while surface water vapor pressure of the materials P_s could be neglected. The relation of these EMPD functions shows in Fig.1.

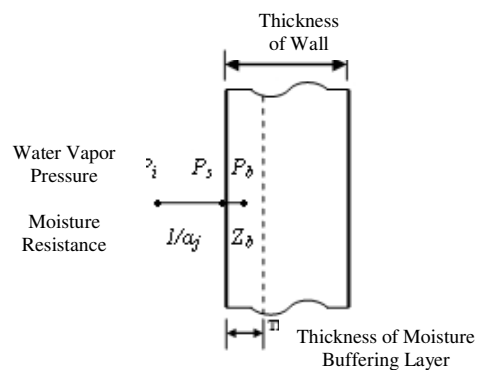


Fig. 1 Diagram of the surface relation in EMPD

Thus, (1) and (5), ordinary differential equations in terms of time as a function, could solve P_i and $P_{b,j}$, when the number of

moisture buffering surfaces is j , and $j+1$ is the solution of the equations. If we assumed that the indoor condition is not isothermal, the temperature of (5) comes from the energy conservation equations of different walls, so the moisture capacity is the function of relative humidity in the surface moisture buffering layer.

This study is based on EMPD and uses EnergyPlus as a tool. However, while setting the parameters in EnergyPlus, for defining the sorption isotherm under the balance equation to calculate the relation between moisture content of the material and the relative humidity of surrounding air, the correlation coefficients, which come from moisture content variation by temperature variation, are needed to setup the simulation. Equation (6) is the moisture balance equation.

$$U = a\phi^b + c\phi^d \tag{6}$$

Where the a , b , c , and d means the coefficients of moisture content of the material and the relative humidity of surrounding air, U is the moisture content of material (kg/kg), and ϕ presents the relative humidity of surrounding air

III. MODEL SETTINGS

A. Space and Materials

The model of this simulation is a typical housing room unit. Fig.2 shows the geometry of the room. The floor area is 20m² (4m×5m), and the area of window opened toward south is 2m² (2m×1m). There is a wood door on inner of the entrance. The ceiling height is 2.5m; thus, the volume of the room is 50m³. The material details are listed in Table 1.

B. Schedule

This study simulates the moisture production rate in a typical housing room unit based on the schedule of two occupants [15]. The basic moisture production rate is 0.5g/m³h. At 6 a.m. to 8 a.m., the moisture production rate is set as 8g/m³h because of the activities, such as washing up or coffee making, after the occupants wakeup in the morning; the moisture production rate is about 4 g/m³h at 4 p.m. to 10 p.m. due to the activities after work. The moisture production schedule is based on Fig. 3.

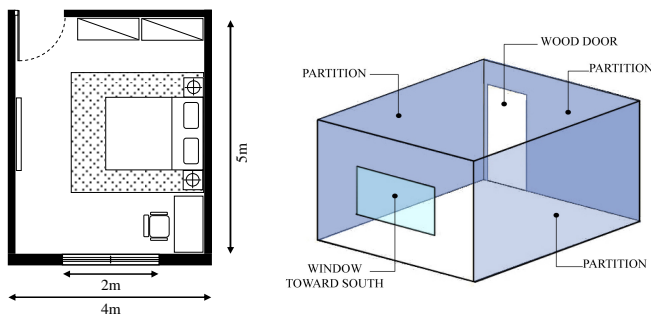


Fig. 2 One-zone model geometry

TABLE II
THE CORRELATION CO-EFFICIENT OF THE EMPD METHOD SETUP IN ENERGY PLUS

Pine Wood	Unit	Value
EMPD	m	0.0004
coefficient a	--	0.11779
coefficient b	--	1.75040
coefficient c	--	0.11779
coefficient d	--	1.75040

C. Coefficients of Moisture Balance Equation

In this study, researcher use Pine wood as the interior EMPD material. The properties of the pine wood are listed in Table 1. For solution of a, b, c, and d in equation (6), researchers use Microsoft Excel program, the tool excel solver, to look for the least square method and the correlation coefficient R. The solution shows in Fig. 4 and Table II.

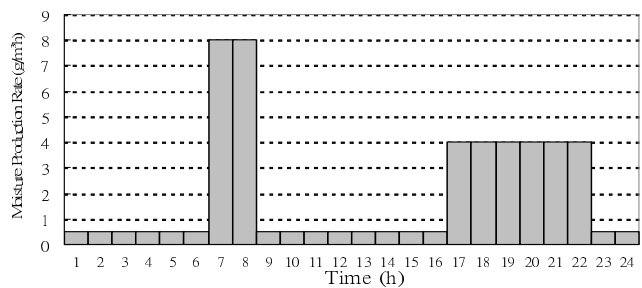


Fig. 3 Schedule of moisture production

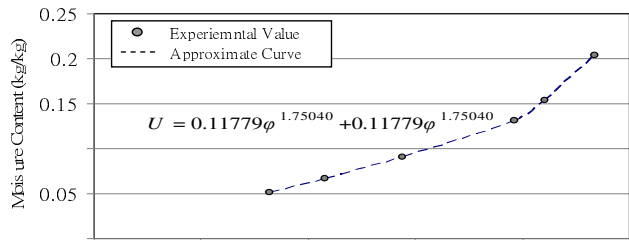


Fig. 4 The approximate cure of the moisture content in pine wood

D. Cases Setup

This simulation is calculated by using the Taipei yearly weather data provided by DOE. The simulation will be presented in both summer (July 4th to 8th) and winter (December 7th to 11th). There are 5 setups of study cases (Table III).

Although EnergyPlus combines the EMPD into the moisture calculation, there are not case studies with moisture buffering provided on the official website of DOE.

TABLE I
LIST OF MATERIALS

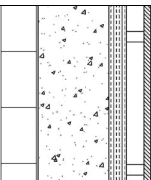


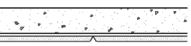
Location	Detail Section	Material	Thickness (m)	Conductivity (W/m/K)	Density (kg/m ³)	Specific Heat (J/kg/K)	Thermal Resistance (m ² /K/W)
External Wall		Brick	0.1016	0.89	1920	790	-
		Concrete	0.2032	1.95	2240	900	-
		Insulation	0.0508	0.03	43	1210	-
		Air Space	-	-	-	-	0.15
		Gypsum Board	0.019	0.16	800	1090	-
Interior Wall		Pine Wood	0.0254	2.05	565	1880	-
		Brick	0.1016	0.89	1920	790	-
		Pine Wood	0.0254	2.05	565	1880	-
Interior Floor		Acoustic Tile	0.0191	0.06	368	590	-
		Air Space	-	-	-	-	0.18
		LW Concrete	0.1016	0.53	1280	840	-
Interior Ceiling		LW Concrete	0.1016	0.53	1280	840	-
		Air Space	-	-	-	-	0.18
		Acoustic Tile	0.0191	0.06	368	590	-

TABLE III
SETUPS OF 5 STUDY CASES

	Moisture Setup A	Moisture Setup B	EMPD	Objective
Case 01	×	×	×	Sensible heat calculation without both moisture production and moisture buffering materials
Case 02	○	×	×	Calculation with basic moisture production but without moisture buffering materials
Case 03	○	○	×	Calculation with both moisture production but without moisture buffering materials
Case 04	○	×	○	Calculation with basic moisture production and moisture buffering materials
Case 05	○	○	○	Calculation with both moisture production and moisture buffering materials

Moisture Setup A : Basic Moisture Production Rate is 0.5 g/m³h

Moisture Setup B : Moisture Production Rate is 8 g/m³h at 6a.m. to 8a.m. and 4 g/m³h at 4p.m. to 10p.m. (Fig. 3)

○ : ON × : OFF

Moreover, most studies, which use EMPD in EnergyPlus, are only discussed regarding the moisture content variation inside the materials; the moisture variations of zones are rarely discussed. Therefore, researchers attempt to simulate indoor temperature and humidity condition by the performance of moisture buffering materials.

IV. RESULTS AND DISCUSSION

A. Confirmation of Model Setup (Case 01, 02, and 03)

The objective of the operations of Case 01, 02, and 03 is because of the references regarding EMPD by EnergyPlus are few.

Therefore, the researchers attempt to operate a pre-model to verify the accuracy of the method. First of all, Case 01-03 are to confirm the model setup. In these 3 cases, the EMPD is off, which means the material does not performance the hygrothermal effect. Besides confirming the moisture variation without moisture buffering materials, also the result shows that the indoor air humidity issue is very serious.

Fig. 5 and Fig. 6 are the temperature and humidity results of July. From Fig. 6, we could see there in no obvious differences of temperature between Case 01, 02, and 03. The reason is that if the materials do not present the moisture buffering performance, moisture content could not affect the indoor heat balance.

Besides, the variation of relative humidity follows the indoor moisture production (Fig.6). The RH of Case 03 is higher than the other two cases due to the moisture production with occupants' schedule. This result shows the setup of fundamental simulation is correct. Therefore, the researchers found that the moisture that comes from the activities of occupants is an essential influence of indoor high humidity. Fig. 6 shows the RH is extremely high, even reaching to 100%, during some periods of a day.

B. Comparison of Case 02 and 04

Fig. 7 presents the comparison of the indoor condition with basic moisture production (0.5g/m³h) with or without EMPD performance. The RH curve of Case 04 shows the moisture buffering pine wood is not only moderate the moisture variation, but, in most periods, the RH of Case 04 is lower than Case 02, which illustrates that the pine wood do carry out the capability of moisture buffering.

C. Comparison of Case 03 and 05

Fig. 8 presents the comparison of the indoor condition with moisture production following the schedule of occupants with or without EMPD performance. The RH curve of Case 05 shows the moisture buffering pine wood is not only moderate the moisture variation, but when curves of RH rise, Case 05 with moisture buffering pine wood is lower than Case 03. This demonstrates the pine wood do carry out the capability of moisture buffering. The similar result of winter season shows in Fig. 9.

However, from both Fig. 8 and 9, the results show that in July 4th to 8th indoor relative humidity is mostly higher than 70%, and the RH in December displays the similar result. Hence, the results demonstrate that even though moisture buffering material could moderate the variation of RH, but indoor air RH remains extremely high condition. This means that, for reducing entire humidity of indoor environment, other design strategies should be added into the indoor environment.

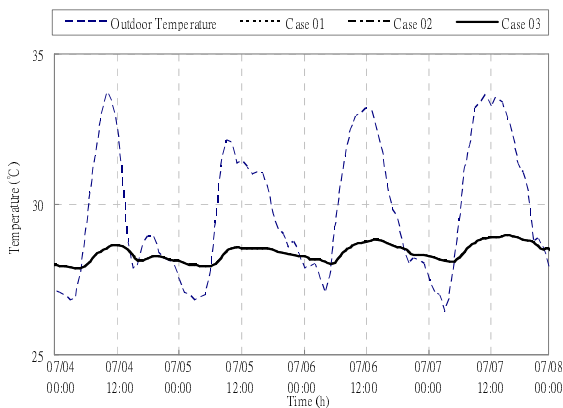


Fig. 5 Indoor and outdoor temperature variation of Case 01-03 (July)

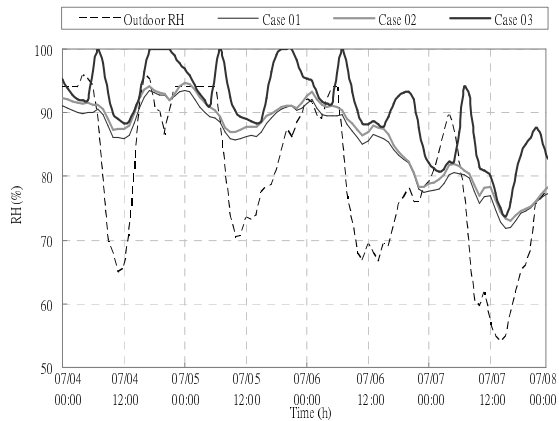


Fig. 6 Indoor and outdoor relative humidity variation of Case 01-03 (July)

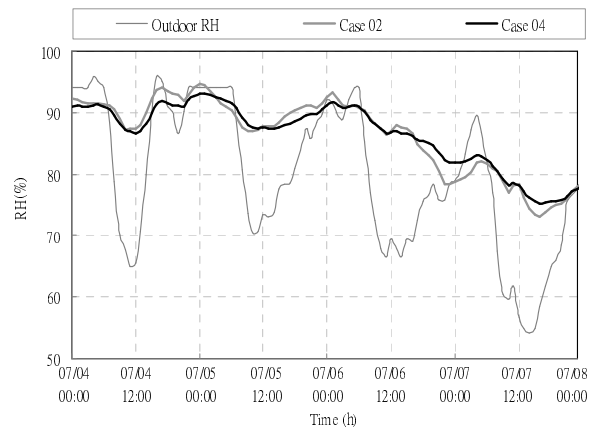


Fig. 7 Indoor and outdoor relative humidity variation of Case 02 and 04 (July)

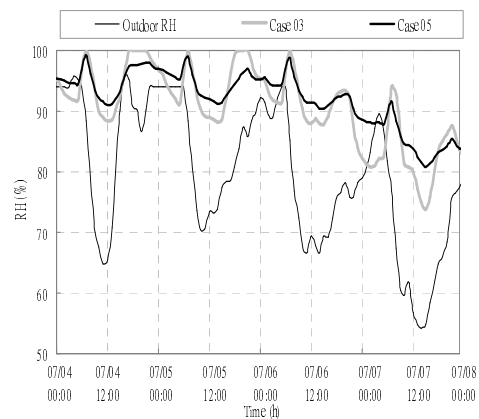


Fig. 8 Indoor and outdoor relative humidity variation of Case 03 and 05 (July)

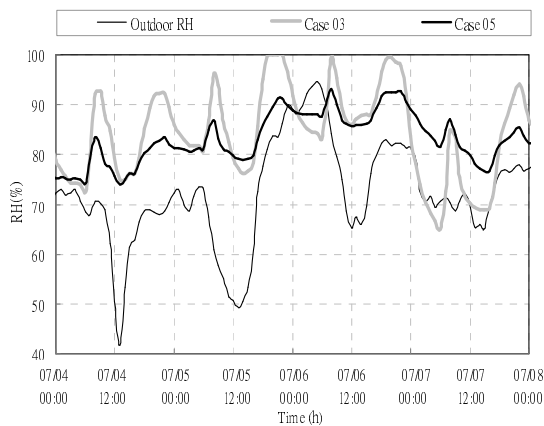


Fig. 9 Indoor and outdoor relative humidity variation of Case 03 and 05 (December)

D. Indoor air quality evaluation

Humidity is an important parameter, which causes serious problems to human and buildings. Accordingly, moisture-buffering effect should be carried out to solve the issue. Table 4 demonstrates the percentage of relative humidity appears during a whole. The researchers also studied in 5 cases in the previous paragraphs. According to Table 4, the RH in all cases is mostly around 70-99%, which is much higher than the 40-70% standard. Compared Case 03 and 05, the results show that moisture buffering materials reduces the percentage of 100%RH from 18.98% to 10.27%, which presents moisture buffering effect performance of the material. However, even moisture buffering reduce the percentage of the highest RH, the RH still remains high, where mostly around 90-99%RH (43.82% of the year). The comparison of Case 02 and 04 is in the similar situation. The results mean that to achieve the effective moisture buffering effect should not only use moisture buffering materials but the other building passive design strategies will be needed, such as ventilation. This result also shows that ventilation is extremely important, which will be the future task of the research.

V. CONCLUSION

Taiwan locates in subtropics, which represents a high temperature and high humidity climate phenomenon. The high temperature and humidity here present a serious indoor air quality issue, which will cause bio-pollution and harmful for human health; it will also cause construction problem, such as the decay and ruin of building materials.

Therefore, how to apply moisture buffering materials practically into the indoor environment should be carried out.

In this research, the simulation bases on the EMPD method which was performed by EnergyPlus, a simulation tool developed by DOE. The researchers attempt to compare the moisture buffering performance of pinewood under different moisture condition setup, to confirm feasibility and practicability that the EnergyPlus applied to moisture buffering simulation of interior materials, and to suggest an ordinary, reliable, and useful simulation tool with accuracy regarding moisture buffering to architecture related industries for supporting building design process.

First, though the reference reviews, the researchers verify the EMPD method and the correlation factors in the simulation. Secondly, the simulation model is based on typical housing room unit built as a one-zone model; the moisture production is based on the typical daily schedule of occupants, which is 8g/m³h at 6 a.m. to 8 a.m. and 4 g/m³h at 4 p.m. to 10 p.m. The simulation is operated as 5 cases with and without EMPD. Finally, researchers discuss the results of the 5 case studies.

Therefore, according to the reference reviews, EMPD is an effective method of calculating moisture content, and could be operated easily to simulate the moisture variation of indoor environment by supporting program. Also, EnergyPlus is verified as a feasible tool to carried out the EMPD, and it is a intermediate-level tool compared to other HAM tool, which means it is easier to implement and suitable for practical design process.

Additionally, the results from 5 cases demonstrate that:

1. The crucial impact factor of the indoor moisture variation is the activities of occupants; and the indoor RH is all exceeded the standard of indoor air quality.
2. Moisture buffering materials could reduce the high humidity obviously.
3. According to the results, pinewoods could response and moderate the indoor moisture variation. However, the effect of the moisture buffering materials is not significant. Thus, other possible methods, such as ventilation, should be considered while doing the practical design.

Consequently, the researchers expect to suggest strategies for reducing the entire indoor RH effectively by combining the moisture buffering materials with practical design method; also, we attempts to implement the multi-zone models simulation in the future to propose the most effective and suitable moisture buffering methods for residential buildings in Taiwan.

TABLE IV
RELATIVE HUMIDITY PERCENTAGE OF THE YEAR

% of the year	RH(%)					
	<40	40-70	70-79	80-89	90-99	100
Outdoor	0.05	18.98	23.81	32.29	23.64	1.22
Case 01	0	12.28	24.60	37.10	17.32	8.70
Case 02	0	10.62	20.81	38.23	19.82	10.53
Case 03	0	4.71	10.97	31.20	34.12	18.98
Case 04	0	7.59	22.08	45.13	20.64	4.57
Case 05	0	1.78	7.99	36.13	43.82	10.27

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REFERENCES

- [1] B. Meyer, "Indoor Air Quality", *Addison-Wesley, Reading, Mass.*, 1983.
- [2] A.V. Arundel, E.M. Sterling, J.H. Biggin, and T.D. Sterling, "Indirect Health Effects of Relative Humidity in Indoor Environments", *Environmental Health Perspectives*, Vol. 60, pp. 351-361, 1986.
- [3] C.G. Bornehag, J. Sundell, S. Bonini, A. Custovic, P. Malmberg, S. Skerfving, T. Sigsgaard, and A. Verhoeff, "Dampness in buildings as a risk factor for health effects", *EUROEXPO: a multidisciplinary review of the literature (1998-2000) on dampness and mite exposure in buildings and health effects*, *Indoor Air*, Vol.14:243-257, 2004
- [4] The Ministry of Health, Labor and Welfare of Japan, website: www.mhlw.go.jp/english/index.html.
- [5] Health Canada, "Exposure Guidelines for Residential Indoor Air Quality – A Report of the Federal-Provincial Advisory Committee on Environmental and Occupational Health", April 1987.
- [6] "Code of Practice for Indoor Air quality for Air-Conditioned Buildings", *Singapore Standard SS 554:2009*, 2009.
- [7] P.C. Wu, H.J. Su, and C.Y. Lin, "Characteristics of indoor and outdoor airborne fungi at suburban and urban homes in two seasons", *The Science of The Total Environment*, Vol. 253, Issues 1-3: 111-118, 2000.
- [8] P.F. Chi, "Fungal Growth on Building Materials", Master Thesis of National Cheng Kung University, 2003.
- [9] Y.S. Tsay, C.M. Chiang, and Y.C. Yeh, "Numerical study on the influence of moisture buffering effect and energy impact of interior materials in hot and humid climates" *Indoor Air 2011, Austin*, Jun. 5-10, 2011.
- [10] Y.C. Yeh, Y.S. Tsay, and C.M. Chiang, "Study on the Performance and Application of Interior Moisture Buffering Materials for the Typical Housing in Taiwan", *Advanced Materials Research*, Vol. 250-253, *Advanced Building Materials*, May, 2011, pp.3723-3729
- [11] H. Hens, "Impact of adventitious ventilation on the moisture performance of roofs in moderate climates", 2003
- [12] M. Abadie, J.P. Deblois, N. Mendes, "A comparison exercise for calculation heat and moisture transfers using TRNSYS and PowerDomus." *IEA Annex 41 report A41-T1-Br-05-2*, 2005.
- [13] A. Kerestecioglu, M. Swami and A. Kamel, "Theoretical and Computational Investigation of Simultaneous Heat and Moisture Transfer in Buildings: Effective Penetration Depth Theory." *ASHRAE Winter Meeting, Atlanta, GA*, 1989
- [14] A. Janssens, M. Woloszyn, C. Rode, A. Sasic-Kalagasidis, and M.D. Paepe, "From EMPD to CFD- overview of different approaches for Heat Air and Moisture modeling in IEA Annex 41" *Copenhagen, IEA ECBCS Annex 41 Closing Seminar*, June 19, 2008
- [15] H.M. Kumzel, A. Holm, D. Zirkelbach, and A.N. Karagiozis, "Simulation of indoor temperature and humidity conditions including hygrothermal interactions with building envelope", *Solar Energy*, Vol. 78, pp.554-561, 2005.