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Indoor Thermal Performance Analysis of Vegetated Wall based on CFD Simulation

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ABSTRACT

In tropical countries, cooling loads have become the largest energy consumption in many buildings. The increase of thermal resistance of the building envelope surfaces will reduce the thermal losses and in that way it improves the thermal indoor climate. Vertical greenery systems have been considered as one of the design trends in the field of architectural and construction for increasing building thermal performance. However, the record of such study is very much limited especially in assessing its performance and also to consider the use of CFD Simulation as validation purpose. This study discussed on the effect of vegetated wall to improve building thermal performance. A CFD Simulation was conducted to assess the effects of vegetated wall on the indoor thermal performance of a building model by setting the thermal properties of vegetated wall. Results of data simulation was compared to data from field measurement. Based on CFD Simulation showed the interior surface temperature of bare wall model was dominant in the range between 28.0°C to 32.2°C. While the lower result showed by vegetated façade with 28.0°C-28.5°C. In the field data measurement, the overall room temperatures in the model with vegetated wall are in the range between 23.0°C to 24.7°C. As for bare wall model, the distribution of indoor temperatures is 26.4°C to 30.2°C. According to the horizontal and vertical distribution of indoor thermal environment, it shows that both interior surface temperature and indoor temperature of building model was much lower after greenery applied. The function of vegetated wall can reduce indoor temperature by 1.7°C, played a natural cooling effect for the room. Through CFD simulation, bare wall had a greater potential for increasing temperature through the building façade. The role of vegetated wall gives significant effect in cooling and insulation of building.

Keywords:
CFD simulation; building model; indoor thermal performance; vegetated wall

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1. Introduction

Building Indoor Environment could be described as one of the most important studying points for designers that must be achieved in highest possible level [1]. In other hand, greenery on the building was introduced in some cities as part of strategy to improve the quality of urban environment. Green roof and vertical greenery system have quickly spread in many modern cities to bring back nature. Compare to green roof, vertical greenery system has huge potentials to utilize thermal performance on the building since façade area is wider than roof area [2]. Summaries based on the Chen *et al.,* [3] there are three kind of vertical greenery systems

a. Green façades refer to attaching climber plants which are planted directly in the ground or in the planter boxes, and are managed to grow directly on building surfaces or by using wire or trellis frameworks as supporting material [4-6].
b. Living wall was constructed from modular panels along with watering system. The vegetation placed in the substrate inside the modular panel and attached on the walls. Usually, living walls use small vegetation such as small shrubs and grass that naturally do not grow higher [4-7].
c. Bio wall is a kind of vertical greenery systems that applied on the interior wall surface [5,6].

Over the decade, number of studies on the vertical greenery system seem to increase. To organize the previous studies, a total of nine (9) review studies were shown in Table 1.

Table 1
Significant previous studies on the use of vertical greenery system as passive design cooling in building

Authors	Publication year	Location	Method	Results
MacPerson [8]	1988	USA	Experimental Simulation	The plants on the west wall were found to be the most efficient in reducing cooling loads. While the heating loads were reduced from south and east wall.
Holm [9]	1989		Experimental Simulation	The vegetation cover had a larger effect on the indoor temperature of low-mass buildings.
Suzuki [10]	2007	Japan	Experimental Simulation	The temperature of area in the town model was decreased by maximum 2.0°C when the surfaces of the roof, south and west walls of buildings were covered by greenery.
Bass [11]	2007	Canada	Experimental Simulation	The green wall showed the insulation effects and reduction of wind chill.
Laopanitchakul *et al.,* [12]	2008	Thailand	Experimental	Surface temperature reduction in the exterior and interior side depending on the quantity of leaves coverage area
Wong *et al.,* [2]	2010	Singapore	Experimental	Each of vegetated wall has different thermal performance due to various factor such as substrate type, structure insulation of vegetated wall, substrate moisture, shade and insulation from greenery
Rosenlund *et al.,* [13]	2010	Sweden	Simulation	No significant impact was shown on building energy performance when it was insulated to current Swedish standards and 3kWh/m^2 savings by green wall was calculated on a building model without insulation.
Widiastuti *et al.,* [14]	2018	Indonesia	Experimental	Model with green facade has lower surface temperature and indoor air temperature than model without green facade

Widiastuti *et al.,* [15]	2018	Indonesia	Experimental	Higher leaves densities possibility can create a better cooling effect but also has the risk of creating higher relative humidity, especially for the interior air layer

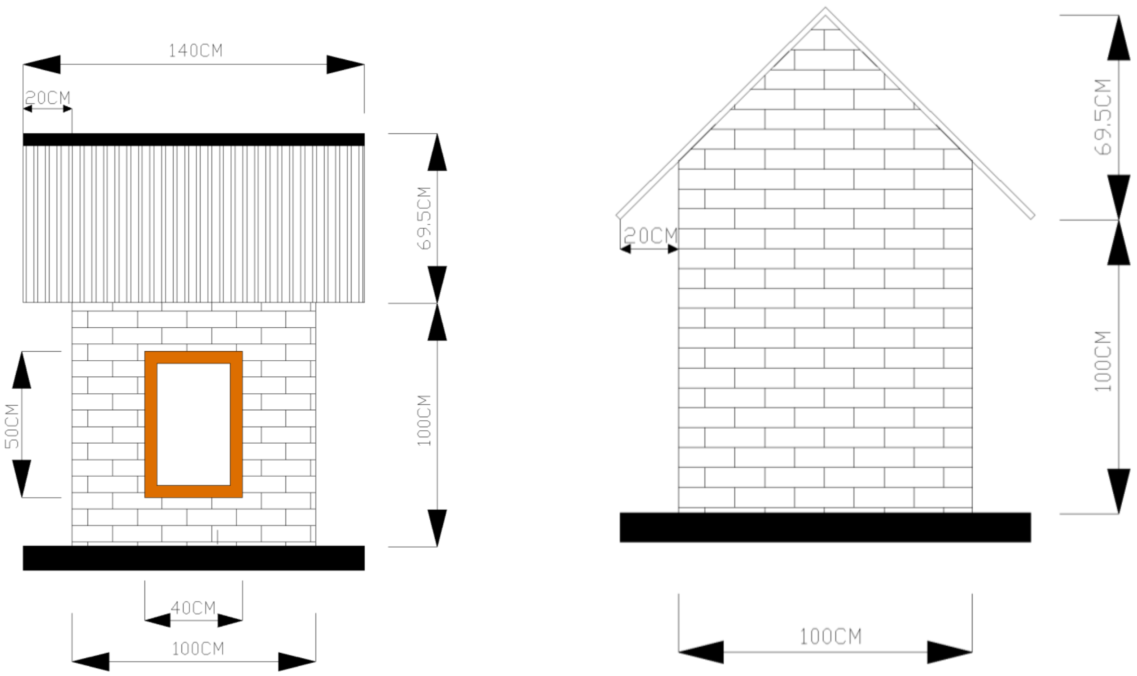
From this overview, along with experimental studies, a few simulation methods have been conducted to evaluate the thermal impact of vertical greenery systems. In some of these simulation methods also discussed energy saving based on the energy flows through the building walls.

As general overview, the authors of this paper previously conducted an experimental study used a scaled building model 1m x 1m x 1m [14-16]. To prove thermal performance of vertical greenery systems, a green façade directly attached in the east façade of building model. The result shows the lowest heat flux (0.60 W/m^2) occurred in the façade with the greatest leaves coverage area.

In order to improve the analysis of previous study, in the paper, a CFD simulation was conducted. Comparing to other computer simulation, CFD simulation can predict the indoor climate in the whole building [17]. Risberg *et al.,* [17] also explained other simulation software do not consider vertical temperature gradient and often only described the indoor climate as a point value in each room. Furthermore, the simulation method was needed to seek the energy flow that occurred through building wall. Considering indoor thermal performance of building, CFD simulation also allows performing comparative analysis based on the different scenarios.

2. Methodology
2.1 Detail of Building Model

This study used CFD simulation based on the experimental study. As for the three dimensional model (3D) was constructed using SolidWorks according to the dimension of building model in the Figure 1 and Table 2. The building model was developed based on the previous experimental studies conducted by Widiastuti *et al.,* (a), Widiastuti *et al.,* (b), Widiastuti *et al.,* (c) [14-16] where some of local climber plants were selected and attaching on the east façade, can be seen in Figure 2.



(a) (b)

Fig. 1. Detail of building model. (a). Front and back view; (b). Side view [15,16]

Referring to the previous study conducted by Nojima and Suzuki [18] the plant in the field measurement consisted of foliage and stems. All of the physical properties of building model were reflected in the calculation of thermal performance in CFD simulation as seen in Table 3. It was assumed as thermal properties of *Ivy hedera helix* leaves.

Table 2
Detail of building model [15,16]

Detail of building model	Specification
Model size	1m x 1m x 1m
Roof material	Asbestos
Roof shape	Gable roof
Wall material	Brick 12 cm
Inlet outlet	Porosity 30 %
Floor material	Concrete
Position of opening	Inlet in the front and outlet in the back

Table 3
Specific of thermal properties of building model [16,19]

	Specification of thermal properties			
	Specific heat capacity	Thermal conductivity	Density of material	U value
Bare wall	900 J/kgK	0.72 W/mK	1900 kg/m^3	0.31 W/m^{2}K
Vegetated wall	2.8 J/kgK	0.36 W/mK	533.280 kg/m^3	0.266 W/m^{2}K
Roof	1.03 J/kgK	0.744 W/mK	245kg/m^3	0.25 W/m^{2}K
Floor	880 J/kgK	0.1 W/mK	1750 kg/m^3	0.62 W/m^{2}K

In this study, U-wert.net was used to calculate U-value of vegetated wall. It was developed by German in order to support calculation of exterior heat and insulation structure [19]. To obtain U-value of vegetated wall, all structure layers of vegetated wall needed to input from inside to outside.

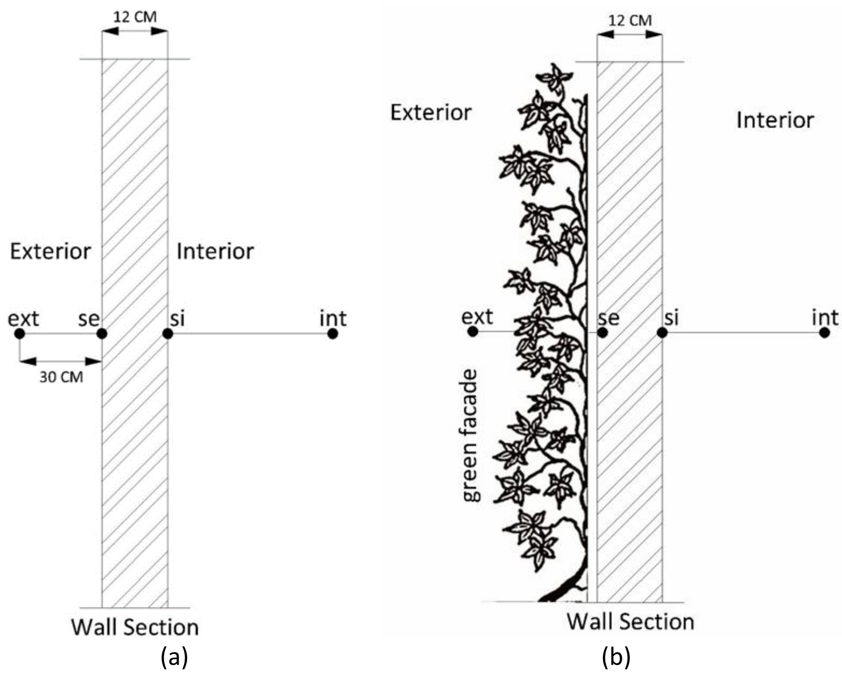
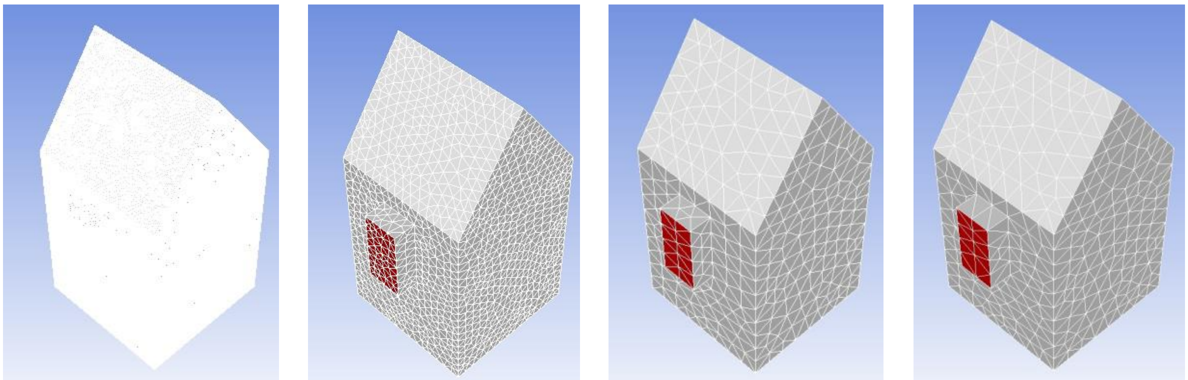


Fig. 2. Illustration of the wall elements with or without green facade: (a). Bare wall section; (b). Green facade section [16]

2.2 Simulation Setup and Grid Independence Study of CFD Simulation

When conducting the simulation study, the construction of the building's exterior walls acts as the major control variables, and other conditions are limiting factors. Two kinds exterior wall structure were determined. One was exterior wall without greening and another one was exterior wall with greening. During data measurement, those two kinds of exterior wall effected the surface temperature of interior wall. In addition, other architectural structures, physical environment, activities and other factors are controlled unchanged [20]. Thus, the changes in eco-effects and quantitative relationship after greening the exterior walls can be obtained.

After determined the boundary conditions, the thermal properties were input into CFD software for geometry meshing. Each of the case studies were simulated in a steady state condition and using the application of k-ε turbulence standard model for fluid flow. Constant velocity magnitude of 1.0 m/s which representing initial condition was used as air velocity inside building models. Based on the data measurement, the surface temperatures of building interior wall were set to 32.0°C for bare wall and 22.0°C for vegetated wall. While external free stream temperature was set to 33.0°C according to the experimental measurement. Before running the solver, the meshing of models, boundaries and cell zones were checked to prevent any errors or floating points occurred during the calculation. The grid sensitivity of the model also was tested. Based on a study conducted by Lin *et al.,* [21] the scales of the grid were tested at 0.01 m, 0.05 m, 0.1 m and 0.5 m which can be seen in Figure 3. Thus, considering the computer performance and computing time, the model grid was generated using a hex grid with a size by 0.01 m. The total cell number of the model was 6.454.237. Finally, CFD simulations was conducted for bare wall model and vegetated wall model according to boundary condition.



(a) (b) (c) (d)

Fig. 3. Grid independence test of CFD simulation: (a). Meshing with grid size at 0.01 m; (b). Meshing with grid size at 0.05 m; (c). Meshing with grid size at 0.1 m; (d). Meshing with grid size at 0.5 m

3. Results and Discussion

Figure 4 and Figure 5 showed the temperature distribution in building models. The different between bare wall model and vegetated model more visible in the pattern of interior surface temperature than indoor temperature. The overall interior surface temperatures of bare wall model are dominant in the range between 28.0°C to 31.0°C, can be seen in Figure 4. While in vegetated model, the result shows the distribution of interior surface temperature was at 28.0°C-28.7°C, can be seen in Figure 5. Based on the CFD simulation, the mean difference of interior surface temperature between bare wall model and vegetated model was range from 0.0°C-2.3°C.

Based on previous study conducted by Lin *et al.,* [21] results from field measurement were used to validate the results of CFD simulation. According to the field measurement, the interior surface temperature of bare wall model is in the range between 28.0°C to 32.2°C and in the vegetated model, the results were 27.0°C to 28.5°C, can be seen in Figure 6. The temperature difference between bare wall model and vegetated model in the field measurement was at 1.0°C-3.7°C. Based on the horizontal and vertical distribution of indoor thermal environment, either result from field measurement or CFD simulation, both proved greenery layer on the building façade can provide lower surface temperature. The absolute error of interior surface temperature between simulation results and field measurement was 1.0°C-1.3°C (relative error was 1.6%-2.2%). This result proved the validity of the simulation.

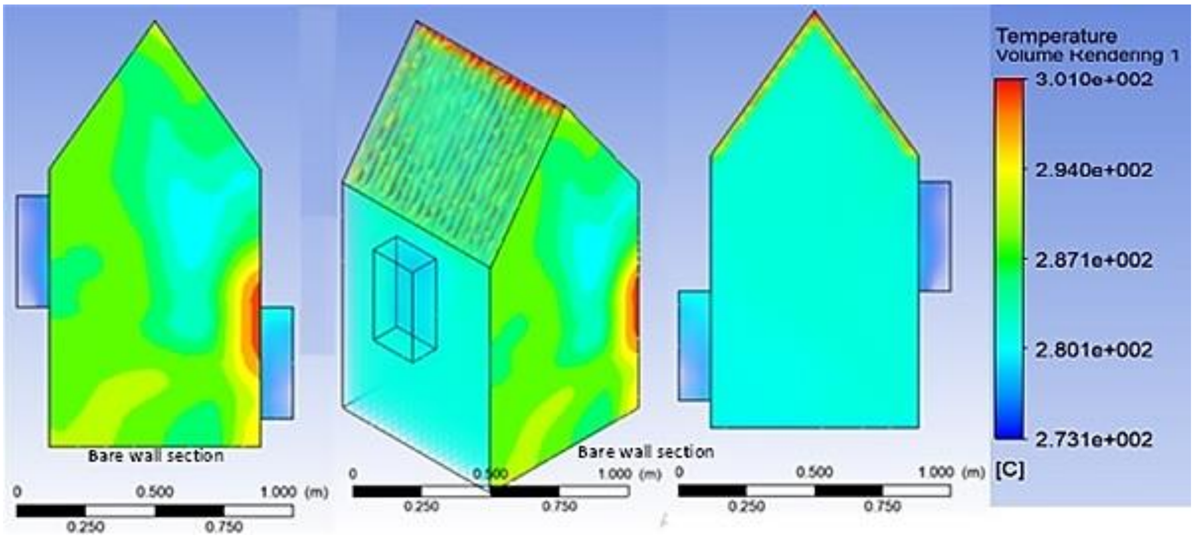


Fig. 4. Simulation result of bare wall model

While the profiles of indoor temperature can be seen in Figure 7 where in the bare wall model the results are 26.4°C to 30.2°C and in the vegetated model are 23.0°C to 24.7°C. The difference of average indoor temperature is 1.7°C and the average of temperature reduction is 3.4%.

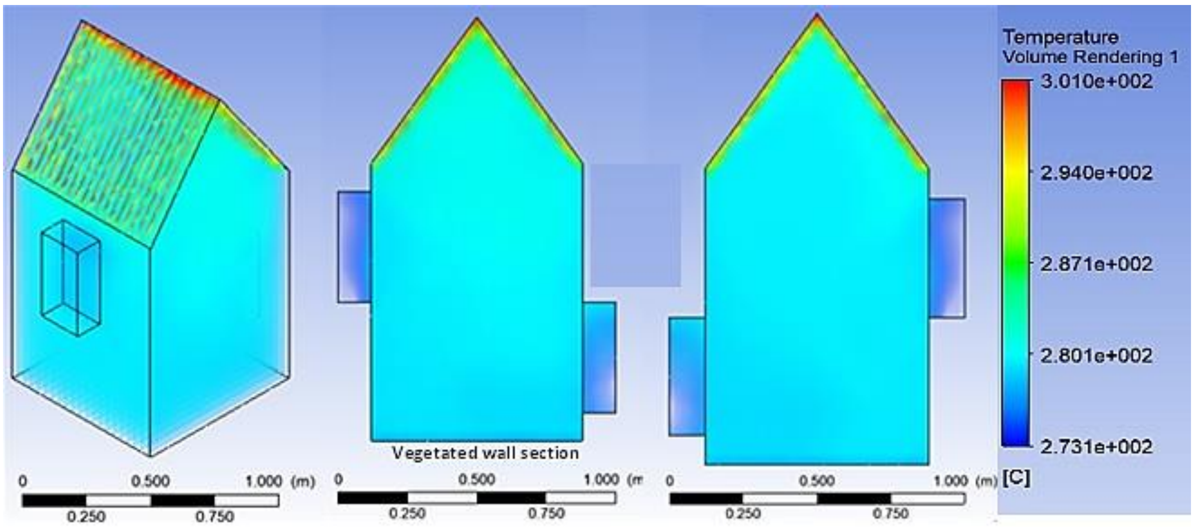


Fig. 5. Simulation result of vegetated wall model

Both of Figure 6 and Figure 7 also presented the highest temperature difference between indoor environment and outdoor environment was recorded during afternoon, approximately 1.7°C to 2.4°C. It means during this time the bare wall model needed more energy to cooling down the indoor environment.

In the end, it can be concluded due to condition that exposed directly to solar radiation, bare wall model had more potential to transfer heat flow to indoor environment. At this point, as vegetated wall can reduce indoor temperature by preventing the overheating of exterior surface temperature. Moreover, evapotranspiration also made the process of heat release on the model occurred more rapidly and reduce the amount of energy from solar radiation [22,23].

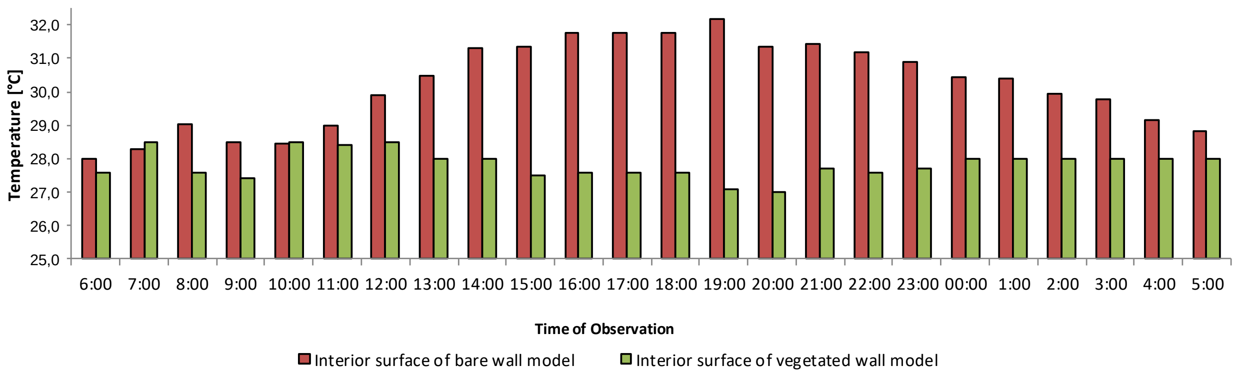


Fig. 6. Profile of interior surface temperature based on the field measurement

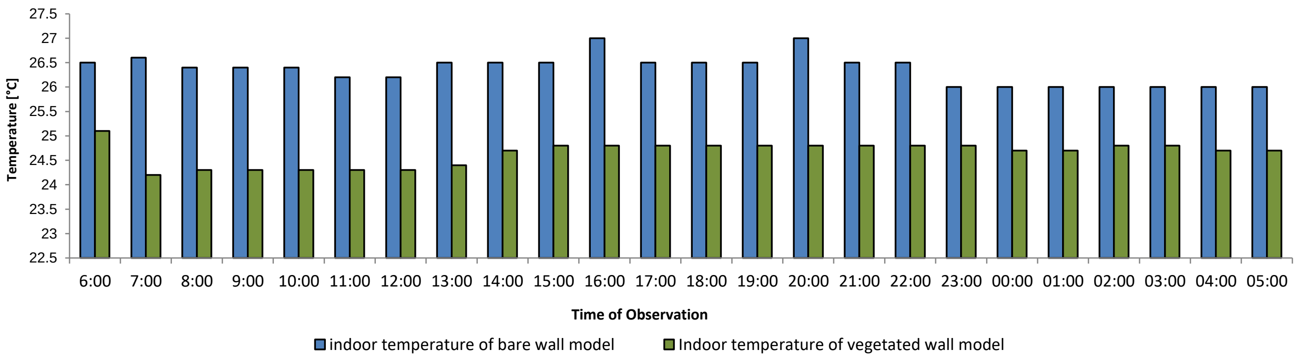


Fig. 7. Profile of indoor temperature based on the field measurement

4. Conclusions

Through the computer simulation software, the weaknesses of theoretical analysis and experimental measurements are overcome. The CFD simulation can equivalently simulate the vegetation stratum on the green facade into a kind of "insulation material" attached to the wall by setting the thermal properties of vegetated wall. The absolute error of interior surface temperature between simulation results and field measurement was 1.0°C-1.3°C (relative error was 1.6%-2.2%). This result proved the validity of the simulation.

Research presented bare wall model had a greater potential for increasing temperature through the building façade. Proved the positive effects of vegetated wall by prevented direct solar radiation and resulting in decreasing temperature on the building. Possibility, heat from exterior blocked by foliage in the greenery system.

The function of vegetated wall can reduce interior surface temperature up to 3.7°C and indoor temperature by 1.7°C, played a natural cooling effect for the room. Result also proved that the vegetated wall reduced the conduction heat gained by building wall. The significant temperature reduction is 3.4% occurred in indoor temperature. Possibility resulted in lower energy consumption for cooling loads.

However, future research is needed to determine the effect of vegetated wall to the indoor thermal comfort, especially related to the profile of indoor air humidity. In order to study of mitigating Urban Heat Island (UHI), this research also will be expanded in the effect of vegetated wall to the outdoor environment near façade.

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References

[1] Morsy, M., M. Fahmy, H. Abd Elshakour, and A. M. Belal. "Effect of Thermal Insulation on Building Thermal Comfort and Energy Consumption in Egypt." *Journal of Advanced Research in Applied Mechanics* 43, no. 1 (2018): 8-19.

[2] Wong, Nyuk Hien, Alex Yong Kwang Tan, Yu Chen, Kannagi Sekar, Puay Yok Tan, Derek Chan, Kelly Chiang, and Ngian Chung Wong. "Thermal evaluation of vertical greenery systems for building walls." *Building and environment* 45, no. 3 (2010): 663-672. https://doi.org/10.1016/j.buildenv.2009.08.005

[3] Chen, Qiuyu, Baofeng Li, and Xiaohu Liu. "An experimental evaluation of the living wall system in hot and humid climate." *Energy and buildings* 61 (2013): 298-307. https://doi.org/10.1016/j.enbuild.2013.02.030

[4] Perini, Katia, Marc Ottelé, E. M. Haas, and Rossana Raiteri. "Vertical greening systems, a process tree for green façades and living walls." *Urban Ecosystems* 16, no. 2 (2013): 265-277. https://doi.org/10.1007/s11252-012-0262-3

[5] Francis, Robert A., and Jamie Lorimer. "Urban reconciliation ecology: the potential of living roofs and walls." *Journal of environmental management* 92, no. 6 (2011): 1429-1437. https://doi.org/10.1016/j.jenvman.2011.01.012

[6] Dunnett, Nigel, and Noel Kingsbury. *Planting green roofs and living walls*. Portland, OR: Timber press, 2008.

[7] Hunter, Annie M., Nicholas SG Williams, John P. Rayner, Lu Aye, Dominique Hes, and Stephen J. Livesley. "Quantifying the thermal performance of green façades: A critical review." *Ecological Engineering* 63 (2014): 102-113. https://doi.org/10.1016/j.ecoleng.2013.12.021

[8] McPherson, E. Gregory, Lee P. Herrington, and Gordon M. Heisler. "Impacts of vegetation on residential heating and cooling." *Energy and Buildings* 12, no. 1 (1988): 41-51. https://doi.org/10.1016/0378-7788(88)90054-0

[9] Holm, D. "Thermal improvement by means of leaf cover on external walls—a simulation model." *Energy and Buildings* 14, no. 1 (1989): 19-30. https://doi.org/10.1016/0378-7788(89)90025-X

[10] Suzuki, H. "Improvement of Urban Environment by Greening Buildings. Review of the effects of building greenery on improvement of thermal environment." *The Japanese Society of Revegetation Technology* 34, no. 2 (2008): 355–362.

[11] Bass, Brad. "Green roofs and green walls: potential energy savings in the winter." *Report on Phase* 1 (2007).

[12] Laopanitchakul, V., P. Sunakorn, and A. Srisutapan. "Climbing-plant on solid wall for reducing energy in tropical climate." In *Proceedings of the International Conference on Sustainable Building Asia, SB07 Seoul*, pp. 271-278. 2007.

[13] Rosenlund, H. "Urban greenery in Sweden, implications for microclimate and energy efficiency." *World Green Roof Congress*. London (2010).

[14] Widiastuti, Ratih, Eddy Prianto, and Wahyu Setia Budi. "Investigation on the thermal performance of green facade in tropical climate based on the modelling experiment." *Int. J. Archit. Eng. Constr* 7 (2018): 26-33. https://doi.org/10.7492/IJAEC.2018.004

[15] Widiastuti, Ratih, Wahyu Caesarendra, Eddy Prianto, and Wahyu Setia Budi. "Study on the leaves densities as parameter for effectiveness of energy transfer on the green facade." *Buildings* 8, no. 10 (2018): 138. https://doi.org/10.3390/buildings8100138
[16] Widiastuti, Ratih, Wahyu Caesarendra, and Juliana Zaini. "Observation to building thermal characteristic of green façade model based on various leaves covered area." *Buildings* 9, no. 3 (2019): 75. https://doi.org/10.3390/buildings9030075
[17] Risberg, Daniel, Mikael Risberg, and Lars Westerlund. "Investigation of thermal indoor climate for a passive house in a sub-Arctic region using computational fluid dynamics." *Indoor and Built Environment* 28, no. 5 (2019): 677-692. https://doi.org/10.1177/1420326X17753707
[18] Nojima, Y., and H. Suzuki. "The effect of the wall greenery for the reduction of the heat flux and the accumulated volume of heat flow toward indoor from the wall in summer." *The Japanese Institute of Landscape Architecture* 67, no. 5 (2004): 447-452. https://doi.org/10.5632/jila.67.447
[19] Pan, Xin Chen, and Yi Xuan Xiao. "Simulation analysis of building green facade eco-effect." In *Applied Mechanics and Materials*, vol. 548, pp. 1701-1705. Trans Tech Publications Ltd, 2014. https://doi.org/10.4028/www.scientific.net/AMM.548-549.1701
[20] Köhler, Manfred. "Green facades—a view back and some visions." *Urban Ecosystems* 11, no. 4 (2008): 423. https://doi.org/10.1007/s11252-008-0063-x
[21] Lin, Hankun, Yiqiang Xiao, Florian Musso, and Yao Lu. "Green Façade Effects on Thermal Environment in Transitional Space: Field Measurement Studies and Computational Fluid Dynamics Simulations." *Sustainability* 11, no. 20 (2019): 5691. https://doi.org/10.3390/su11205691
[22] Scudo, G., and J. M. Ochoa De La Torre. "Spazi Verdi Urbani. Napoli: Se, Rome, Italy." (2003).
[23] Mazzali, Ugo, Fabio Peron, Piercarlo Romagnoni, Riccardo M. Pulselli, and Simone Bastianoni. "Experimental investigation on the energy performance of living walls in a temperate climate." *Building and Environment* 64 (2013): 57-66. https://doi.org/10.1016/j.buildenv.2013.03.005