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To cite this article: H Kitagawa *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **294** 012088

A field experiment on green walls taking into consideration wind flow in the hot-humid climate of Indonesia

H Kitagawa[1], A Tanimoto[2], T Kubota[2,3], K Koyama[4] and MNF Alfata[3]

[1]School of Environment and Society, Tokyo Institute of Technology, 4259 Nagatsuta-cho, Midori-ku, Yokohama, Kanagawa, 226-8503, Japan.
[2]Graduate School for International Development and Cooperation, Hiroshima University, 1-5-1 Kagamiyama, Higashihiroshima, Hiroshima, 739-8529, Japan.
[3]Research Instutute for Housing and Human Settlements, Ministry of Public Works and Housing, Jl. Panyaungan, Cileunyi Wetan, Kabupaten, Bandung, 40393, Indonesia.
[4]Department of Agro-environmental Science, Obihiro University of Agriculture and Veterinary Medicine, Inada-cho, Obihiro, Hokkaido 080-8555, Japan.

Correspondence: kitagawa.h.ab@m.titech.ac.jp

Abstract. This paper presents the results of a preliminary experiment using test cells constructed in Bandung, Indonesia. We particularly analysed the thermal effects by comparing green walls with wooden blinds in contrast with those of no covering materials to determine the factors affecting the improvements of indoor thermal conditions in hot-humid climates. The results showed that, unexpectedly, indoor thermal conditions were not improved when green walls/blinds were installed, at least at the center of the units. Nevertheless, air temperatures behind the green walls were found to be lower than those of the other conditions. Moreover, the factors affecting the Standard Effective Temperature (SET*) were analysed in detail by dividing SET* into four thermal factors in terms of temperature, including air temperature, radiation, humidity and wind speed. The further analysis showed that the increases in SET* in the units with green walls were mainly attributed to the reduction of wind velocities (36–45%). It can be concluded that the airflow blockage effect by the green walls was larger than its transpiration cooling effect at the center of the units.

1. Introduction

In general, passive cooing strategies aim to: 1) minimize heat gain, 2) dissipate internal heat and 3) modulate the heat [1]. Green walls, which are made of plants, are normally utilized in buildings for its shading effects and reduction of surface temperature. The green walls are expected to improve thermal conditions in indoor and outdoor building environments by reflecting solar radiation and reducing heat transfer through the envelopes. Unlike ordinary building materials, leaves can absorb large part of solar radiation for photosynthesis and transpiration [2]. Through the photosynthesis and transpiration, solar radiation energy can be converted into chemical energy and latent heat, and thus it can improve thermal comfort by transpiration cooling. In hot-humid summer of Japan, the research showed that the green walls can reduce the temperature of a veranda that faces south-west [3]. In Singapore, an ambient air temperature reduction up to 3.3°C was observed behind vertical greenery systems [4].

In the hot-humid climate such as Indonesia, in addition to solar shading and temperature reduction, natural ventilation is required for passive design. Ventilation can remove heat from building structure at night, and thus nocturnal ventilation is effective for structural cooling [5]. Meanwhile, it was reported that the residents in Indonesia tend to open windows to let wind enter the rooms for comfort ventilation during the daytime [6]. Meanwhile, the sky solar radiation is generally large in the tropics due to large cloud covers, and therefore an external shading such as green walls can be preferable regardless of the building orientation. However, it should be noted that there is a trade-off between the shading effects and ventilation effects [7].

The aim of this research is to develop a new green wall system that improves indoor thermal environments in the tropics by giving sufficient shading effect and temperature reduction while allowing wind flow, so as to reduce the Standard Effective Temperature (SET*) inside the rooms. This paper presents the results of preliminary experiment using cubic test cells constructed in the city of Bandung, Indonesia. Here, we analyse the thermal effects of green walls in contrast with those of wooden blind windows to determine the factors affecting the improvements of indoor thermal conditions in hot and humid climates.

2. Methodology

2.1. Outline of field experiment

Small-scale test cells (3.0 m × 3.0 m × 2.6 m) were constructed in Bandung, Indonesia (7°S, 107°E), which are identical three cells: two units (Units 1–2) were used as experimental units and the other cell (Unit 3) was used as control unit without attaching any test devices (Figure 1). The test cells were made of brick wall and precast concrete structure, which represent typical urban houses in Indonesia. The thickness of the cement plastered brick wall is 144 mm. All exterior walls were painted with the white paint to have high reflectance and reduce heat gain to the cells. The floor is steed deck slab and reinforced concrete slabs of 150 mm thick. The aluminum roof tiles (1.6 mm thick) were laid on water proof layer (1 mm thick), GRC board (6 mm thick) and wood panel (12 mm thick). The ceiling adopted the GRC board (6 mm thick) with rock wool insulation (100 mm thick) to reduce the heat gain from the roof. Meanwhile, the semi-outdoor space is wooden structure with a deep eave. The roof structure of semi-outdoor space consists of three layers; the GRC board (6 mm thick) with a thin layer of double-sided aluminum foil underneath as a radiant barrier, and the wood panel (12 mm thick).

Table 1. (a) Experimental cases and (b) the surface area and the frontal projection area of test devices.

(a)

	Unit 1 (green wall)			Unit 2 (blind)			Unit 3 (control)
	Material	Amount	Configuration	Material	Amount	Angle	
Case 1	Green	Sparse	Climb	Blind	Sparse	30°	Default
Case 2	Green	Dense	Climb	Blind	Dense	30°	Default
Case 3	Green	Dense	Hung	Blind	Dense	15°	Default

(b)

	Unit 1 (green wall)		Unit 2 (blind)	
	Surface area (cm^2)	Projection area (cm^2)	Surface area (cm^2)	Projection area (cm^2)
Case 1	28,223 cm^2	13,819 cm^2	22,500 cm^2	11,250 cm^2
Case 2	55,168 cm^2	17,803 cm^2	44,250 cm^2	22,125 cm^2
Case 3	51,875 cm^2	11,326 cm^2	44,250 cm^2	11,451 cm^2

Here, we compared the green walls (Unit 1) with the blinds (Unit 2) in contrast with the control unit (Unit 3) particularly in terms of the three effects, i.e. solar shading, wind flow and reduction of indoor temperature (Table 1). In Case 1, the two devices were compared under the sparse shading conditions in which the total surface area and frontal projection area of the devices are approximately 25,000 cm^2

and 12,000 cm^2 respectively. In Case 2, we then increased the density of the devices equally to approximately 55,000 cm^2 and 20,000 cm^2 respectively. Case 3 was conducted to examine the possible improvement of wind flow by changing the plant form from 'climb-up' to 'hang-down' type.

2.2. Description of materials

The test devices, i.e. green wall and blind, were installed vertically on the east side of the test cells with a distance of 40 cm from the external wall. The devices were placed under the eave and towards the prevailing wind direction (i.e. east). The blinds are made of wood to represent similar thermal profiles with those of green wall. *Thunbergia grandiflora* was used for the green walls in this study. It is an evergreen vine and widely known as a fast-growing species. 27 nursery stocks of *Thunbergia grandiflora* were prepared and raised in each plastic container containing Lembang's soil mixed with rice-hulls and compost from June 2018. Until the end of October, the vines reached up to 2.7 m, then carried out the field experiment. 25 nurseries were used as the green walls and the rests were used as samples to measure the total leaf areas through a destruction method based on multiplication of leaf length and leaf width (Table 1b). Meanwhile, the frontal projection area was measured by a non-destructive method using image editing software, which is Adobe Photoshop CC 2018.

2.3. Measurement variables

The field experiment was carried out during a beginning of the rainy season from 1st to 16th November 2018. Data were collected during three periods and each case lasted 3-4 days. The previous study showed that daytime ventilation is common practice of occupants of apartments in Indonesia [5][6]. Nevertheless, all cases were conducted under full-day ventilation to receive the wind in the daytime and adopt the structural cooing effect in the night-time.

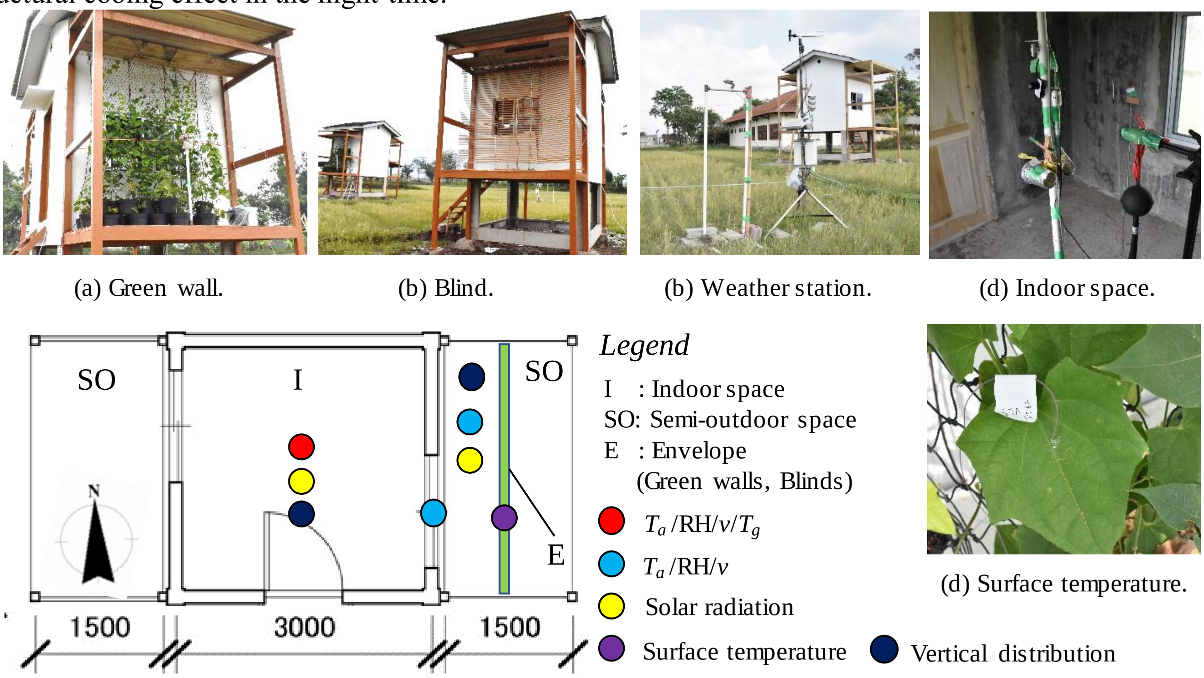

Figure 1. Photographs of the experiment, showing experimental setting.

Air temperature (T_a), relative humidity (RH) and wind speed (v) were measured at 1.1 m height above the floor in the three test cells simultaneously (see Figure 1). Vertical distributions of T_a was examined in the middle of the room and the midpoint between the test device and the wall (i.e. semi-outdoor space). Mean radiant temperature ($\bar{T}_r$) was then calculated by the following equation [8].

$$\bar{T}_r = \left[(T_g + 273)^4 + \frac{1.1\times10^8\times v^{0.6}}{\varepsilon_g\times D^{0.4}}(T_g - T_a)\right]^{1/4} - 273 \qquad (1)$$

where T_g is the globe temperature (°C), v is indoor wind speed (m/s), ε_g is emissivity of the block globe (0.98) (–), and D is the diameter of the globe (m). Outdoor weather condition was recorded with a weather station that was placed in open space approximately 15 m away from the units (Figure 1). The outdoor weather condition was logged automatically at 1 min interval and variables in the indoor and the semi-outdoor space were measured automatically at 30 sec intervals. All the sensors were calibrated by comparing with more accurate sensors such as Assmann aspiration psychrometer.

The performance of the test devices was evaluated mainly in terms of SET* at the center of the rooms. In calculating SET*, the metabolic rate was assumed to be 1.0 met, which indicates seated position. Meanwhile, clothing insulation was estimated to be 0.5 clo, which expresses typical clothing worm when the outdoor condition is warm [9]. Moreover, the factors affecting SET* were analyzed in detail by dividing SET* into four thermal factors in terms of temperature, including air temperature (ΔT), radiation (ΔT_{rad}), humidity (ΔT_{hum}) and wind speed (ΔT_{vel}) [10].

3. Results

3.1. Outdoor weather conditions
The outdoor air temperature during the field experiment ranged from 19.6–32.2°C with the average of 24.1°C, while the outdoor relative humidity ranged between 45.2% and 98.6%. Since the elevation is high, about 760 m, Bandung has a relatively cool tropical climate compared with other major cities of Indonesia. As the rainy season began during the field experiment, most days for measurement had light shower in the daytime, and therefore global horizontal solar radiation was uneven during the period. In sunny days, the maximum global horizontal solar radiation recorded more than 1000 W/m^2. The average outdoor wind speed at the same height of the test cells was 0.95 m/s (Case 1), 0.55 m/s (Case 2) and 0.53 m/s (Case 3) respectively. The main direction of the wind was between NNE and E.

3.2. Indoor thermal environment
Figure 2 shows temporal variation of the thermal environments measured in the middle of the cells at 1.1 m height above the floor. Overall, the average indoor air temperature was around 24.9–25.1°C (Unit 1), 24.6–24.8°C (Unit 2) and 24.7–24.9°C (Unit 3) during the experimental period, respectively. In the daytime, due to the nocturnal ventilative cooling effect, the indoor air temperature maintained lower values than the outdoors even though windows were kept open. In contrast, indoor air temperature in the night-time was 1.4–2.3°C higher than the outdoors. It should be noted that nocturnal air temperature of the Unit 1 was averagely 0.2°C higher than the other units in all cases. This is because the Unit 1 used different instrument (data logger for anemometers) from the other units, causing slight heat generation from it. This affected MRT of the Unit 1 as well. Nevertheless, the said heat gain in Unit 1 did not cause differences among units during the daytime, especially peak hours (when the effects of test devices were assessed), due to relatively large ventilation rates.

In Case 1, which compares green wall and blind in sparse conditions, unexpectedly, daytime air temperature at the center of Unit 1 (green wall) is slightly higher than that of Unit 3 (control) by approximately 0.2°C (Figure 2a). Meanwhile, the corresponding daytime air temperature in Unit 2 (blind) recorded almost the same values as that of Unit 3. Indoor wind speeds were also generally lowered in both Units 1 and 2 compared with Unit 3. The average daytime wind speed is 0.13 m/s in Unit 1, 0.21 m/s in Unit 2 though it is 0.22 m/s in Unit 3. The reason why Unit 1 obtained the lowest average wind speed is probably attributed to the thickness of envelopes (test devices). The thickness of the blind is 2.5 cm, while that of green wall is more than 10 cm. The resulting SET* in Units 1 and 2 are, therefore, approximately 1.0 and 0.3°C higher than that of Unit 3 during Case 1.

Unexpectedly, similar results were obtained in Case 2 as well (Figure 2b). This means that a clear improvement of indoor thermal conditions was not observed even when dense green wall/blind was adopted, at least at the center of units. During the daytime, SET* ranged from 22.4–29.9°C in Unit 1 (green wall) and 21.3–28.8°C in Unit 2 (blind) whereas the corresponding SET* is 19.9–28.9°C in Unit

3 (control). Similarly, the results of Case 3 do not show the improvement in SET* at least at the center of units (Figure 2c).

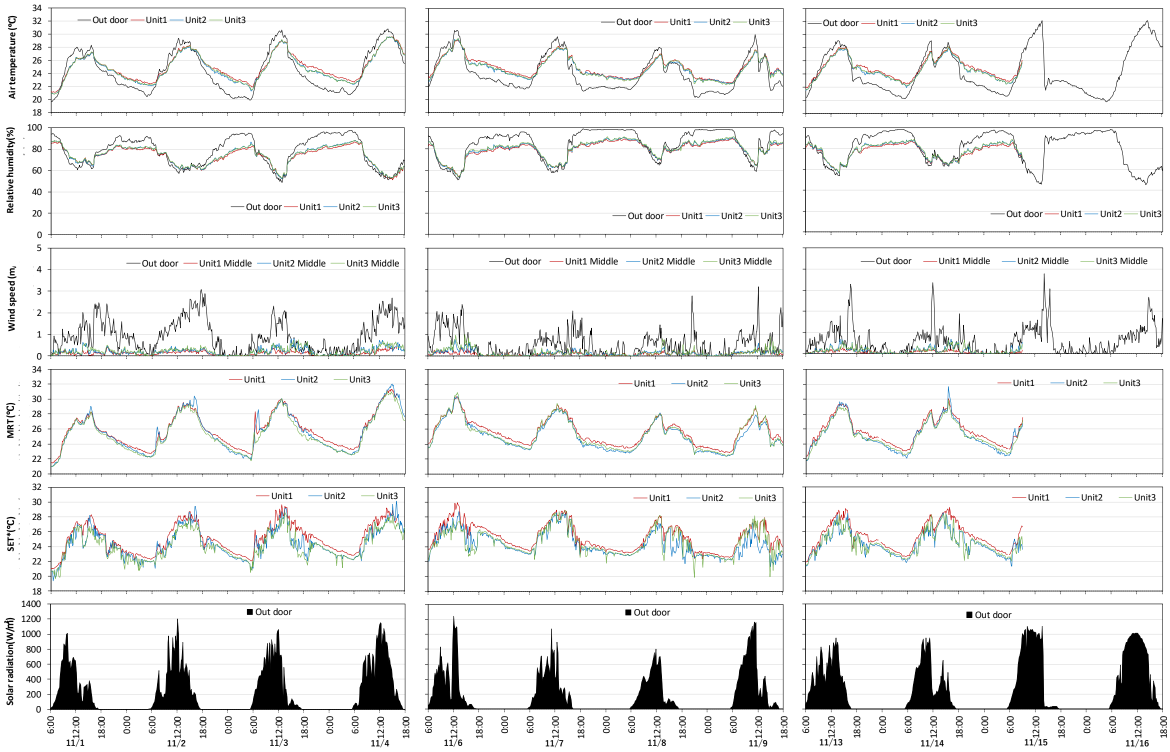

Figure 2. Temporal variations of indoor thermal environments (a) Case 1; (b) Case 2; (c) Case 3.

3.3. *Vertical distribution of air temperature in the indoor space and the semi-outdoor space*

Figure 3 presents the vertical air temperature distribution in the indoor space and semi-outdoor space of the units during peak hours in Cases 1-3, respectively. Throughout the cases, the surface temperatures of floor inside the units ranged between 26.5°C and 27.6°C regardless of the units, which are approximately 0.42–0.91°C lower than the ambient temperatures except Case 2 due to the thermal mass effect. The effects of air temperature reduction due to the test devices (i.e. green wall/blind) can be seen at the semi-outdoor space, which was 20 cm behind the devices. Particularly at the heights of 1.4–2.7 m above the floor, in Cases 1–3, the peak air temperatures in that space in Unit 1 (green wall) is approximately 0.19–0.94°C lower than the corresponding air temperatures of Unit 3 (control). This indicates the cooling effects caused by the transpiration. On the other hand, the same air temperatures in Unit 2 (blind) are higher than those of Units 1 and 3. This is probably because the blinds received solar radiation and reduced wind flow, resulting in the heat gain in the semi-outdoor space.

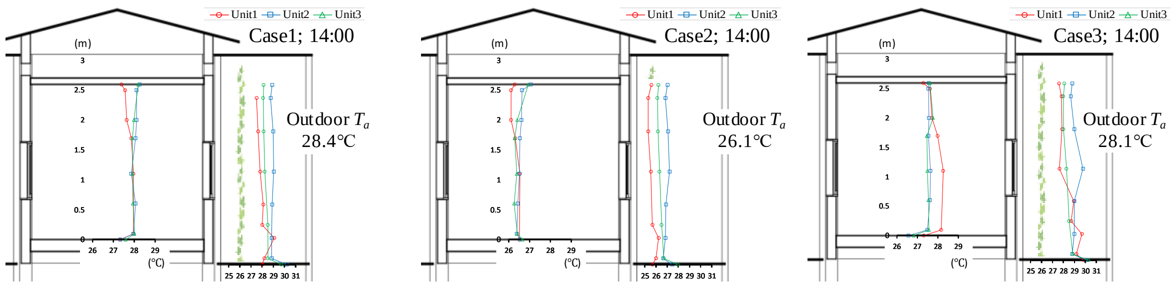

Figure 3. Vertical distribution of air temperature at 14:00 of three units.

4. Discussion

In the following sections, first, we analyse the thermal effects of test devices, i.e. green walls and blinds, in contrast with that of the control unit in terms of shading effect, ventilative effect and temperature reduction. Second the factors affecting SET* are analysed in detail by dividing into four thermal factors, i.e. air temperature (ΔT), radiation (ΔT_{rad}), humidity (ΔT_{hum}) and wind speed (ΔT_{vel}).

4.1. shading effects

Figure 4a shows the ratio of vertical solar shading measured at the middle of the units in Cases 1–3. The shading ratio (R_{solar}) was calculated by the following equation.

$$R_{solar} = 1 - \frac{Q_{Test}}{Q_{Control}} \quad (2)$$

where Q_{Test} is vertical solar radiation of the experimental units (W/m^2), and $Q_{Control}$ is solar radiation of the control unit (W/m^2).

Basically, the test cells have deep eaves at the semi-outdoor space, and therefore inside of the units could avoid direct solar radiation most of the time. Hence, the test devices reduced mainly the sky solar radiation. Therefore, the shading ratios of all cases were relatively low values compared with the previous simulation results [7]. The above results also show that the angle and width of louver are crucial for solar shading effects.

As shown in Figure 4a, for each of the test devices (i.e. green wall and blind), the solar shading ratio is associated with its frontal projection area. As expected, the solar shading ratio increases with the increase in its projection area, although the total surface areas little affected the solar shading ratios.

Nevertheless, even when the frontal projection areas are approximately the same between the two devices, the green walls obtained larger solar shading ratios. The difference of solar shading ratio between the two devices is probably caused by the fact that leaves of green walls naturally changed its angle toward the sun to optimize the photosynthesis, although the projection areas of the green walls are similar with the blinds. Moreover, as mentioned previously, the difference of thickness between the two devices was also a possible cause.

4.2. Ventilation performance

The effect of ventilation is evaluated for the green walls (Unit 1) by calculating wind velocity ratio (R_{wind}), which is expressed by the following equation.

$$R_{wind} = \frac{v_{cavuty}}{v_{out}} \quad (3)$$

where where v_{cavity} is the wind speed measured in the semi-outdoor space (m/s) and v_{out} is outdoor wind speed (m/s). As expected, the highest wind ratio is obtained in the default measurement, in which the green walls were not installed. As shown in Figure 4b, the wind velocity ratios were decreased by approximately 18% when the dense green walls were installed (Case 2), but the reduction was only 7% in the case of sparse green wall (Case 1). Interestingly, the wind velocity ratios were increased as the form of plants was changed from “climb-up” to “hung-down” type mainly due to the reduction of airflow resistance.

4.3. Reduction of temperature

Figure 4c shows a relation between the measured total transpiration rate and the difference of surface temperature of green walls compared with the corresponding surface temperature of blinds. As shown, the difference of surface temperature, i.e. cooling effect, increases with the increase in transpiration rate of plants.

Figure 5 presents the horizontal distribution of air temperature in the three units at 14:00 for Case 1–3, respectively. As discussed before, the reduction of air temperature due to the test devices cannot be seen clearly at the middle of the rooms. However, the difference of air temperature can be seen clearly particularly in the semi-outdoor space (20 cm away from the test devices) for all the cases. Since Unit 3 (control) did not install any devices, the air temperatures at the semi-outdoor space were almost the same as the corresponding outdoor air temperatures in all the cases. Meanwhile, the cooling effects of the green walls were observed in Case 1-3. The air temperature at the semi-outdoor space in Unit 1 (green

IOP Conf. Series: Earth and Environmental Science **294** (2019) 012088 doi:10.1088/1755-1315/294/1/012088

wall) at 14:00 was lower compared with the control unit by 0.29°C in Case 1 (sparse), 0.83°C in Case 2 (dense climb-up) and 0.67°C in Case 3 (dense hang-down), respectively, on average.

In contrast, the air temperature in Unit 2 (blind) at the semi-outdoor space was approximately 0.79-1.49°C higher than Unit 3 (control) at 14:00 on average. However, the said air temperature increases at the semi-outdoor space did not affect the indoor air temperatures at the middle of the rooms. This indicates that cooled and warmed air caused by blinds/green walls did not reach even the windows thus inside the units.

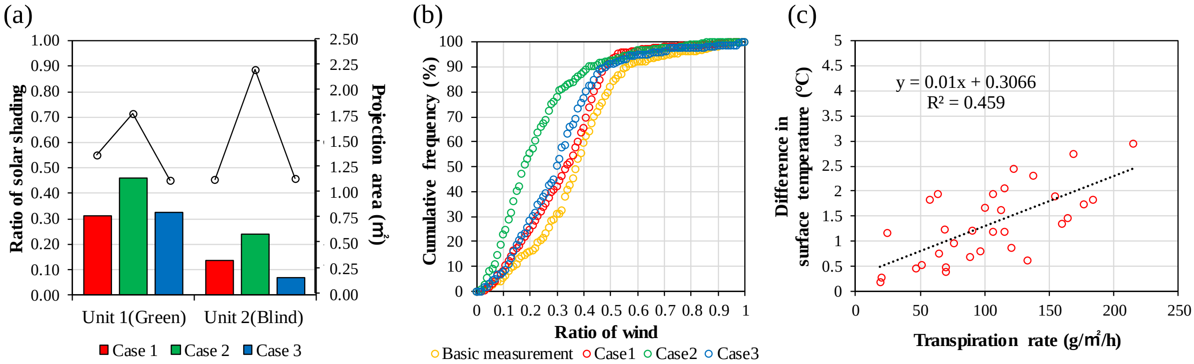

Figure 4. Evaluation the preferable functions of the green walls; (a) Solar shading; (b) Ventilation performance in Unit 1; (c) Relation between transpiration rate and difference of surface temperature of envelopes.

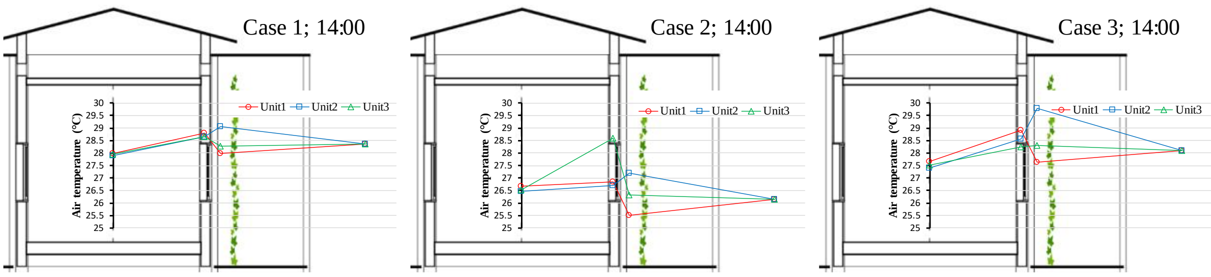

Figure 5. Horizontal distribution of air temperature of three units at 14:00.

4.4. SET evaluation*

Basically, SET* measured at the center of units is used as a single thermal comfort index to evaluate thermal environments comprehensively. Then, we analysed the detailed influences on SET* by dividing into the said four thermal factors as shown in Figure 6. The four thermal factors are expressed in terms of temperature in the experimental units (Unit 1–2) compared with the control unit (Unit 3).

Overall, the measured SET* ranged from 25.1–25.4°C in Unit 1 (green wall), 24.4–24.9°C in Unit 2 (blind) and 24.1–24.9°C in Unit 3 (control) during the measurement period, respectively. As described before, SET* in Unit 1 was slightly higher than the rest of the units especially during the night-time due to unexpected heat generation from the instruments. This unexpected increase can be seen not only in temperature effect (ΔT) but also in radiation effect (ΔT_{rad}) as shown in Figure 6a. Except for the above increase, the increases in SET* in Unit 1 are mainly attributed to the reductions of wind velocities (36%–45%) in all cases. Because of the hot and humid conditions, the reduction of wind velocity strongly affects the indoor thermal comfort. It can be concluded that the airflow blockage effect by the green walls was larger than its transpiration cooling effect at the center of the units. Transpiration is the process that carry moisture from roots to stomata then releasing vapor in exchange for absorbing heat from ambient air. The average humidity effects (ΔT_{hum}) in Unit 1 are slightly higher (0.01–0.02°C) than those of Unit 2 ((-0.01)–0.00°C) on the other hand.

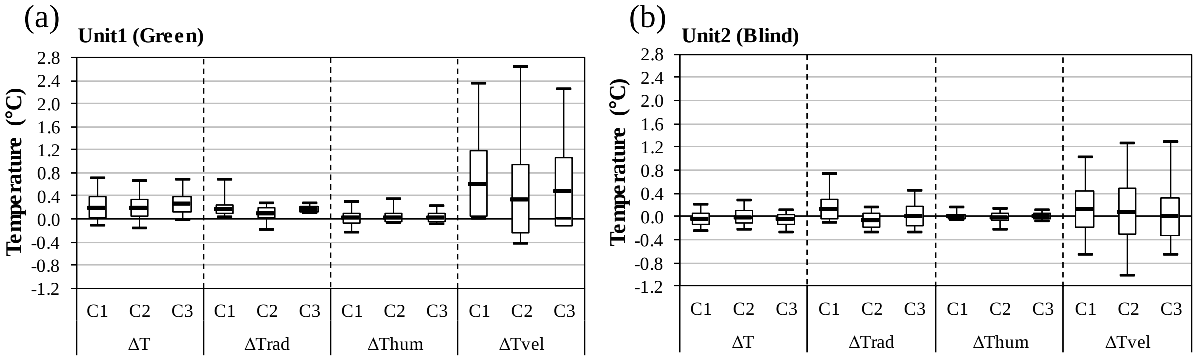

Figure 6. Detailed influences on SET* by comparing between (a) Unit 1 and Unit 3; (b) Unit 2 and Unit 3

There was no clear difference in the indoor air temperature between Unit 2 and 3, even though the air temperature at the semi-outdoor space in Unit 2 was higher than the corresponding outdoor air temperature (Figure 6b). As explained before, the test cells have eaves providing sufficient shade which can avoid the direct solar radiation at the semi-outdoor space, and therefore the radiation effect for SET* was not large in all cases. Nevertheless, it can be seen in Unit 2 that the radiation effects in Cases 2–3 (dense shading) were approximately 0.12–0.20°C lower than those of Case 1 (sparse). This suggests that in the tropics, a shading device needs to consider the sky solar radiation as well as the direct solar radiation due to relatively large cloud cover.

5. Conclusions

This paper represented the results of preliminary experiments using test cells constructed in Bandung, Indonesia. Particularly, we analysed the thermal effects of green walls in contrast with those of blinds to determine the factors affecting the improvements of indoor thermal conditions in hot-humid climates. The main findings are summarised as follows:

- Unexpectedly, indoor thermal conditions assessed by SET* were not improved when green walls/blinds were attached, at least at the center of the units. For example, in the case of sparse shading condition, the resulting SET* in Units 1 (green wall) and 2 (blind) was approximately 1.0 and 0.3°C higher than that of Unit 3 (control) during daytime.
- The said improvement was not observed even when the dense green wall/blind was adopted nor when liana plants with different forms ('climb-up' to 'hang-down') were used.
- Nevertheless, it was observed that air temperatures behind the green walls (20 cm away from the green walls) were lower than those of the other conditions. For example, the air temperature behind the green walls was 0.29°C lower than the control unit in the case of sparse plants, 0.83°C lower in dense climb-up plants and 0.67°C lower in dense hung-down plants at 14:00 on average, respectively.
- For each of the shading devices, the solar shading ratio was found to be associated with its frontal projection area, and the green walls obtained relatively larger solar shading ratios than those of blinds even when the projection areas are almost the same between the two devices.
- As expected, the wind velocities were decreased by approximately 18% when the dense green wall was installed, but the reduction was only 7% in the case of sparse green wall.
- The further analysis showed that the increases in SET* in the unit with green walls were mainly attributed to the reduction of wind velocities (36%–45%). Because of the hot-humid conditions, the reduction of wind velocity strongly affects the indoor thermal comfort. It can be concluded that the airflow blockage effect by the green walls was larger than its transpiration cooling effect at the center of the units at least for the present experimental set up.

Acknowledgements
The authors would like to thank the Research Institute for housing and human settlements, Ministry of Public works of Indonesia, for providing construction site of the experimental cells. We also thank David

Campbell in Obihiro University of Agriculture and Veterinary Medicine for editing the part of the manuscript draft. This research was not possible without financial supports from YKK AP.

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