平成 28 年度 風工学研究拠点 共同研究成果報告書

研究分野：室内環境
研究期間：平成 28 年度
課題番号：152007
研究課題名（和文）：亜熱帯気候におけるマンションベランダ緑化が室内温熱環境に与える影響（その２）シミュレーションによるベランダ緑化の年間熱負荷削減の確認

研究課題名（英文）：The influence of vertical greenery on mansion balcony to indoor thermal environment in sub-tropical climate areas. Part 2: simulation of the reduction of annual heat load by vertical greenery

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１．INTRODUCTION

Research of greenness in building had been studied and showed the results of how greening could improve our living environment. Cameron et al. (2014) studied different types of vertical greenery such as green walls and showed that the wall with plants covered was cooler up to 3°C. To evaluate the mitigation effect of urban heat island, Misaka et al. (2006) executed the field measurement and the analysis of heat balance of a wall greening system, the results also showed that the evapotranspiration rate played an important role in heat flux.

However, the evapotranspiration rate depends on several factor such as species, LAI (leaf area index), as well as climate factors. Baille et al. (1994) measured nine ornamental species evapotranspiration rate and found that factors related to climate were solar radiation and VPD (vapor pressure deficit). The past research has proposed that the weight difference of plants could be measured to estimate the evapotranspiration rate in different climatic conditions. By statistical analysis, Chang et al. (2002) found that solar radiation and VPD were the major factors in evapotranspiration mechanism and had less relations to soil temperature and wind speed. Huang et al. (2010) did the field measurements to estimate evapotranspiration rate of arbors in Japan climatic conditions. The study found that evapotranspiration had significant correlation to solar radiation, VPD and ambient temperature, but not wind speed.

Studies on evapotranspiration model of plants for vertical greenery in Taiwan were relatively less. This study focuses on single potted plant which is common in Taiwan, such as wild allamanda and then proposed the simple model of evapotranspiration rate under Taiwan climatic conditions for designer to use as references.

The use of vertical greening design on building has been a topic of research to improve the heat island effect in dense cities. Wang et al. (2010) found that vertical greenery could decrease the air temperature near the plants, thus place the air intakes of air-conditioning at right position can reduce the energy consumption of buildings.

A vertical greenery system provides the effects of shading, evapotranspiration and reduction of wind speed, which lead to the influence of thermal comfort. Wang et al. (2009) found that a liner correlation between shading coefficient and leaf area index where a lower shading coefficient leads to a greater thermal insulation. Jim et al. (2011) also found that building envelope strongly correlates with canopy transmission and reflectance and solar radiation. Salisbury et al. (1976) found that evapotranspiration is an important heat transfer way when plant conduct in nature. The heat balance would influence by factors such as solar radiation, convection heat transfer and evaporation latent heat. Misaka et al. (2006) estimated the heat balance of vertical greenery and found that indoor temperature attenuation was influenced by evapotranspiration rate. Results show that evapotranspiration rate was influenced by the environmental factors such as wind velocity or solar radiation.

With a population density of exceeding 600 people/km^2, high-rise buildings is the main building type in the major cities of Taiwan. Balconies with depth are commonly used in building design for shading, and thus provide the potential of the vertical greening design. However, evapotranspiration model of plants in Taiwan for balcony greenery system was rare for design studies.

In this study, an evapotranspiration model of wild allamanda (*Urechites lutea*), a sub-tropical trailing plant, was developed by field measurement, and the effects of temperature/wind reduction were verified by experiment and simulation. The measurement of evapotranspiration was then carried out again in another season for verification. The model then applied in CFD, and a field measurement was carried out and the results of temperature and wind velocity were compared to ensure the applications of simulation. Finally, the model was used in a practical design work for studying the improvement of thermal comfort by balcony greenery.

2. METHOGOLOGY

2.1 The measurement of evepotraspiration rate

The experiment was located in National Cheng Kung University, Tainan, Taiwan and took place at the roof floor of Earthquake Engineering laboratory, where could not be shaded by other buildings during experiment time.

The cylindrical form of experimented flowerpot was 16 cm (height) × 18 cm (diameter). The horticultural soil, which is commonly used, was chosen to be the substrate for potted plants. The pot was wrapped with aluminium foil to prevent from solar radiation and sealed the opening to avoid direct evaporation from soil. The plants were controlled in 60 cm (height) × 30 cm (diameter).

The plant was watered and the soil moisture was controlled. The plant was weighted by electronic scale for measuring the weight loss as evapotranspiration each hour. As shown in Figure

1, the weather station was located near the plant, and recorded environment factors hourly including wind speed, solar radiation, temperature, and relative humidity. Data were collected during 10:00 am to 5:00 pm in 2014 autumn and 2015 spring. Table 1 shows the measurement factors and used instruments. The process for evapotranspiration was based on measured meteorological parameters and weight differences each hour. Multiple regression analysis was used to define the relationship between evapotranspiration and the environmental factors.

A evapotranspiration model was proposed after the measurement, and the other field measurement was carried out In 2015 autumn with the same dimension of pot but different wild allamanda for validation.

Figure 1. Diagram of potted transpiration measurement

Table 1. Measurement factors and instruments

Measurement factors		Instruments	Units	Interval
Evapotranspiration rate	Soil moistures Weight change	soil moisture sensor electric scale	% g/h	60 min
Environmental factors	Wind speed Solar radiation Ambient temperature Relative humidity	weather station	m/s W/m^2 °C %	10 min

2.2 The field measurement for the validation of CFD simulation

The experiment was conducted in autumn, including field measurement and properties experiment of plants. A local plant, wild allamanda, was used for the greening design in this study. 12 units of the same size pot planting were set up on the balcony for experiment and simulation. The space of the experiment is a west balcony with an indoor corridor. A weather station was installed on the roof for meteorological factors. Moreover, an actinograph was set on the balcony above the floor for 150cm to measure solar radiation. The temperature and wind velocity were measured by thermo-couple and anemometer. Figure 2 shows the experimental setting on floor plan. 10 points were set for temperature measurement, and 3 points were set for wind velocity measurement.

The evapotranspiration rate, porosity and leaf area were also measured to be parameters in CFD, as shown in Table 2. PHOENICS was used to simulate the changes of temperature and wind velocity when air flowed through the plants into balcony and interior. Considering the experimental space, a west balcony where plants will be radiated directly in the afternoon, eight sessions with different weather conditions were selected for comparison. The boundary conditions are shown on Table 1. The simulation size of domain was 3.4m(W)×3.5m(H)×10m(L) and the sum of grid was about 450,000.

In CFD, the heat flux and porosity of plant was set for simulating the activities of plants. The measured evapotranspiration rate was converted to heat flux set in simulation. The correlation between conduct heat and superficial area would not be considered while heat flux of porous media was set. Therefore, the equivalent conduct heat conversion to multiplied evapotranspiration rate and superficial area rate were needed. Thus, the converted evapotranspiration heat was the heat flux in simulation.

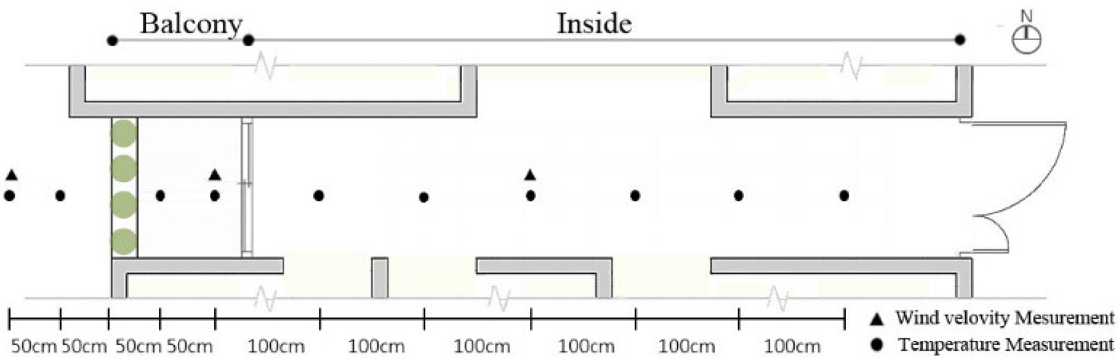

Figure 2. Experimental space plan

Table 2. Boundary conditions of simulation

Time	Heat Flux	Porosity	Inlet		
			Temperature	Velocity	Turbulence Intensity
	W/per unit	-	°C	m/s	-
11/08 14:00~15:00	-23.51	High face 0.282 East face North face 0.254 Volume 0.991	26.5	0.55	74%
11/08 15:00~16:00	-16.51		26.2	0.51	66%
11/09 14:00~15:00	-26.25		27.6	0.54	53%
11/09 15:00~16:00	-32.26		27.8	0.56	84%
11/16 14:00~15:00	-17.34		26.0	0.51	80%
11/16 15:00~16:00	-15.03		25.2	0.48	52%
11/30 14:00~15:00	-25.69		29.5	1.06	62%
11/30 15:00~16:00	-27.35		29.3	1.02	50%

2.3 A Case Study of Architectural Design

After the comparison of the experiment and CFD simulation, the results were used as basis of greening design and thermal comfort regarding natural ventilation was evaluated. A practical project was selected to study the effect of vertical greenery on thermal comfort. This reform project is an exhibition center, which located in Nantou with a latitude of 23°58´ north and longitude of 12°58´ east.

The project was an exhibition center for flower, and a large area of windows was designed for efficient day lighting, and thermal comfort was not an important issue in original design. In the reform project, the usage was planned for a tourism factory with a space for workshop and activities. The design strategy of vertical greenery system with natural ventilation was studied for improving thermal comfort and energy conservation.

July 2015 weather data was obtained from Taiwan Central Weather Bureau, and the boundary conditions are shown in Table 3. An inner heat source of 200 visitors was applied to the second floor. Two vertical greenery systems with each 100 plants were applied at the balcony of second floor to study the improvement of thermal comfort, as shown in Figure 3. A case without vertical greenery (current status) was also carried out for comparison.

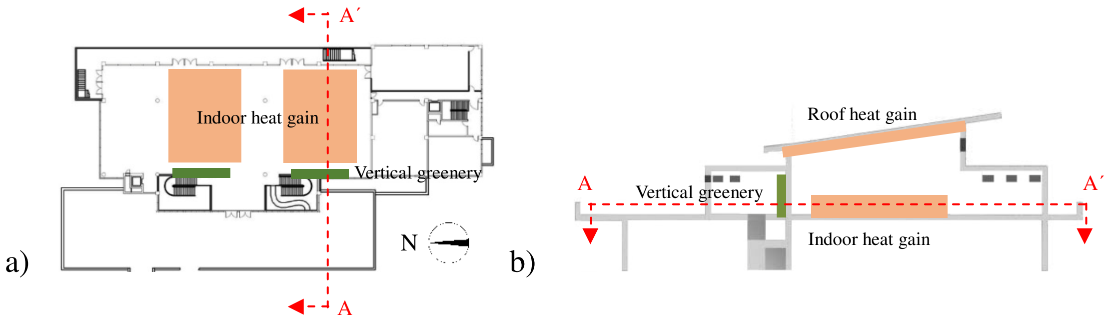

Figure 3. Second floor plan and section of exhibition center

Table 3 . Boundary conditions of simulation

Heat Source			Porosity			Exterior conditions		
Roof	People	Plant	Top	Side	Volume	Temperature	Velocity	Direction
W/m^2	W/person	W/unit	-	-	-	°C	m/s	-
6.39	50	-32	0.282	0.254	0.991	28	1.57	northwest

3． RESULTS AND DISCUSSION

3.1 Relations between evapotranspiration and environment factors

The relations between evapotranspiration and environment factors are shown in Figure 4. The wind speed has little correlation to evapotranspiration (R^2=0.0106). Evapotranspiration has correlation to solar radiation (R^2=0.585), VPD (R^2=0.474) and ambient temperature (R^2=0.479).

To develop a evapotranspiration model of wild allamanda, solar radiation, VPD and temperature can be used for the equation. However, according to Baille et al. (1994), the influence of temperature and humidity are included in VPD, thus evapotranspiration rate (E, g/h) can only be determined by the factors of solar radiation (G, W/m^2) and VPD (Pa), and the equation based on the measurement is shown as Eq.(1),

$$f(E) = aG + bD \tag{1}$$

where parameter a and b were calculated by the least square method based on the collected data during 2014 autumn and 2015 spring, and the evapotranspiration model is shown as Eq. (2):

$$f(E) = 0.022G + 0.009D \tag{2}$$

In 2015 autumn, the other field measurement was carried out with the same dimension of pot but different wild allamanda, and the data of environmental factors by Eq. (2) was calculated. Compared the actual evapotranspiration to calculated one, the study found that the R^2 =0.704 as shown in Figure 5 was significant correlation. The results showed that the Eq. (2) was feasible which could be used to estimate the evapotranspiration while the climatic conditions could be obtained.

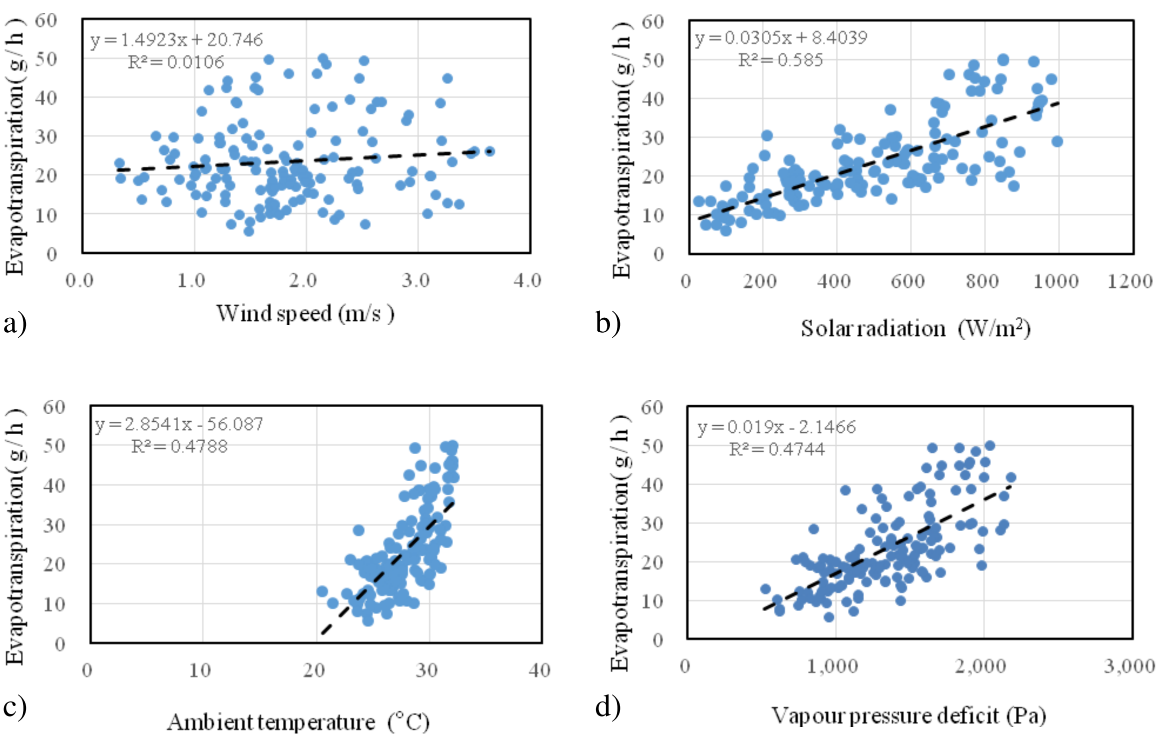

Figure 4. Relation between evapotranspiration and a) Wind speed, b) Solar radiation, c) Ambient temperature, d) VPD.

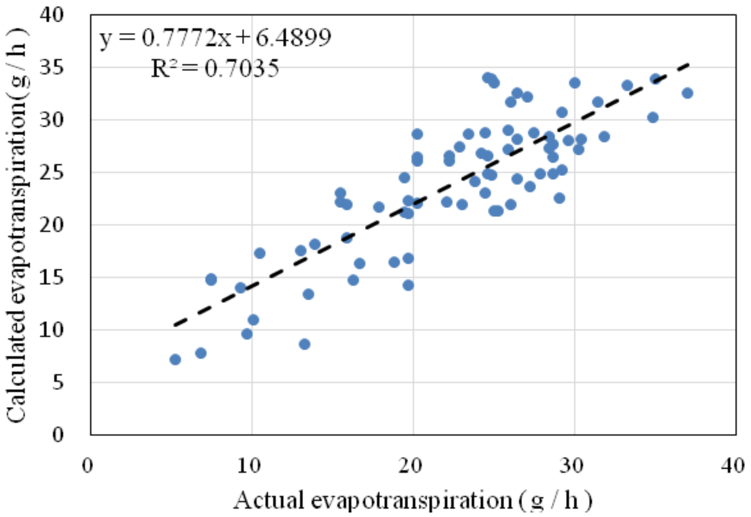

Figure 5. Relation between calculated evapotranspiration and actual evapotranspiration for the period of the experiment in autumn 2015.

3.2 Comparison of field measurement and CFD simulation

For the verification of CFD simulation, Figure 6 shows the results of temperature and wind velocity of field measurement and CFD simulation. The R^2 of temperature and wind velocity are both exceeding 0.9, which showed a high correlation between field measurement and simulation.

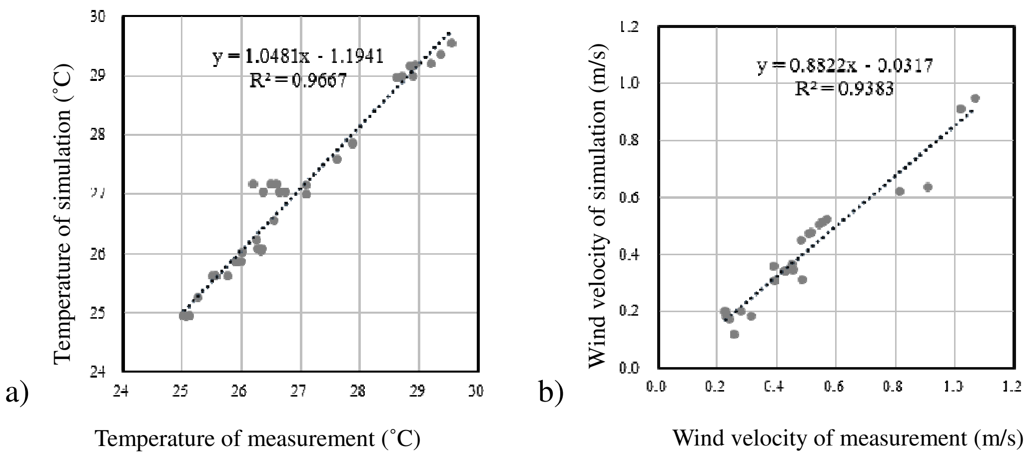

Figure 6. Correlation coefficient of simulation and measurement. a) Temperature, b) Wind velocity

3.3 The case study of an exhibition center

Figure 7-8 show the simulation results of temperature distribution at the second floor. Although natural ventilation from the large area of windows was flow through the space, indoor thermal load still could not be totally removed. In current status, mean temperature above second floor for 1.5m was 28.4˚C, and the maximum temperature was 29.3˚C. After installing vertical greenery systems, mean temperature at 1.5m high was reduced to 28˚C, and the maximum temperature was 28.4˚C. The results show that with vertical greenery, the temperature of air near the plants was significantly reduced, and the indoor mean temperature was also decreased. Although the reduction of mean temperature was around 0.4˚C, but the reduction of maximum temperature was 0.9˚C, which showed that vertical greenery systems could improve the problem of local high temperature regions.

Furthermore, in the case of current status, the distribution of airflow coursed the accumulation of thermal load at the corners of north and south sides. After installing the vertical greenery systems, the mean indoor wind velocity decreased to 0.2m/s and distributed more evenly. This is because the airflow was influenced when passed through the vertical greenery system, thus the distribution of airflow was changed in the second floor and improved thermal comfort.

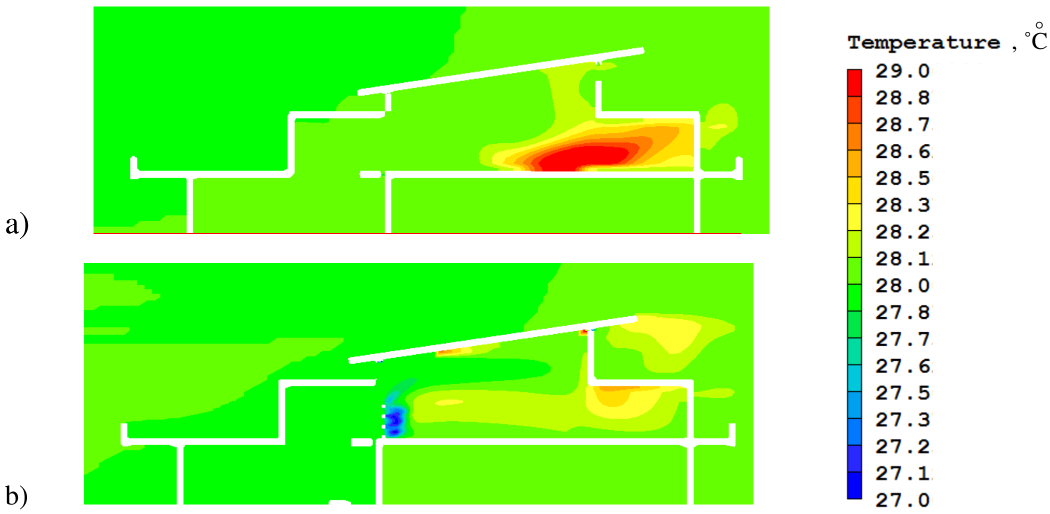

Figure 7. Temperature result of simulation. a) current status, b) vertical greenery

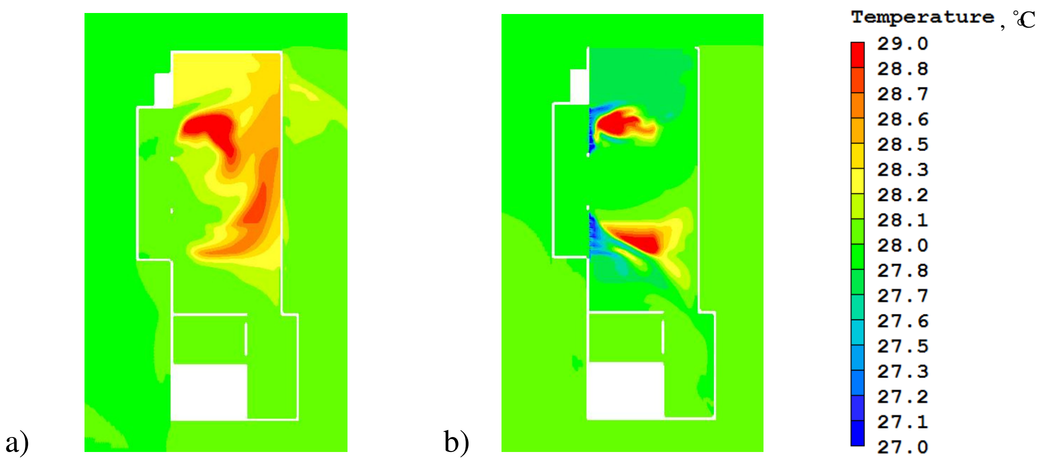

Figure 8. Temperature result of simulation. a) current status, b) vertical greenery

a) b)

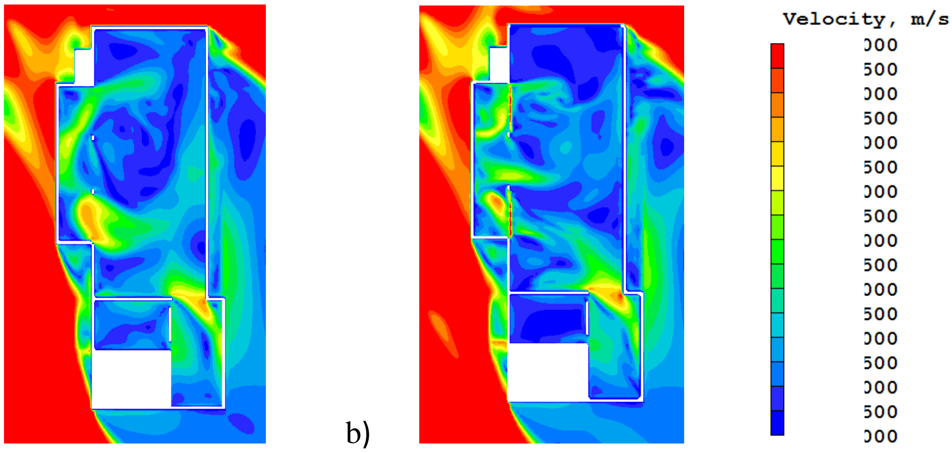

Figure 9. Wind velocity result of simulation. a) current status, b) vertical greenery

4. CONCLUSIONS

In this study, a plant model of evapotranspiration rate was proposed via field measurement and applied for the boundary condition of CFD simulation. The results of field measurement showed that evapotranspiration was an effective factor to the temperature reduction of nature ventilation, and was influenced by meteorological factors, especially the solar radiation and vapour pressure difference.

The phenomena of wind speed reduction and temperature drop when airflow passed through the vertical greenery system was simulated, and verified by a field measurement. Finally, the vertical greenery system was applied to a practical design project for studying the effect of thermal comfort improvement. As the results, the indoor temperature was reduced and the distribution of wind velocity was improved in the CFD study.

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6. PUBLICATIONS

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