Improving Air-conditioners' Energy Efficiency Using Hydroponic Roof Plants

F. Wang and H. Yoshida
Kyoto University

M. Yamashita
Taisei Corp.

ABSTRACT

Experimental study was conducted on improving air-conditioners' energy efficiency using hydroponic roof plants. The air-cooling effect caused by the solar-shading and transpiration of hydroponic-cultivated sweat potato was measured. Using the measured data, it is estimated that how much the energy efficiency of an air-conditioner can be improved if the cooled air is introduced into the outdoor unit of air-conditioners. The measured air temperatures and cooling loads were used to calculate the energy consumption of the air-conditioner. 1) The measurement results show that the air temperature differences cooled down by the roof plant are 1.3^{o}C in average for clear day and 3^{o}C in average when water was sprinkled. 2) The energy consumption estimation shows that about 1%-4% energy can be reduced in clear days and 2%-9% energy can be reduced if one-hour-water-sprinkle is conducted two times a day.

1. INTRODUCTION

Environment and energy issues are considered to be most urgent nowadays even in future. A lot of researches have been conducted to protect environment and reduce energy consumption. In the field of building and urban environment, green roof attracts a lot of researchers' attention because it is considered to be a good solution for improving urban thermal environment by mitigating heat island and to reduce building cooling energy consumption by reducing cooling load. Alexandria et al. (2008) analyzed how much the urban canyon temperature can be decreased due to green walls and green roofs. Takebayashi et al. (2007) compared the building surface heat tranfer of green roofs with common roofs and high reflection roofs. Di et al. (1999) measured an actual green wall to analyze how much cooling effect is achieved. Elena (1998) analyzed the cooling potential of green roofs. Kumar et al. (2005) developed a mathematical model to evaluate the cooling potential and solar shading effect of green roofs. Wong et al. (2003) analyzed the thermal benefits of green roofs in tropical area. Besides studying the green roofs' benefits of heat island mitigation and thermal isolation, the cost vs. benefit is also analyzed (Clerk et al., 2008) and green roof plants selection is analyzed as well (Spala et al., 2008).

However, the research cannot be found on how to improve air-conditioners' energy efficiency utilizing the cooling effect and solar shading of green roof. Therefore this research proposes a system combining the hydroponic-cultivated green roof plants with air-conditioners for the purpose of utilizing the cooling effect and solar shading of green roof plants (Fig. 1). The outdoor unit of air conditioners is set under the plants to let air flow through plants and cooled by plants. Also the plants shade solar radiation to prevent the outdoor unit from absorbing solar energy and raising surface temperature. Compared with soil-cultivated green roof, hydroponic-cultivated green roofs are light enough to set on existing buildings, which did not consider the weight of soil-cultivated green roof plants during design phase so it cannot burden the weight. Furthermore, the hydroponic-cultivated green roof plants are light enough to be able to lifted upon outdoor unit of air-conditioners, which makes the proposed system feasible.

For the purpose of check the energy saving potential of the system, experimental devices are set up on the roof of a five-story office building in Osaka Japan. The air temperature cooled by the green roof plants, plant transpiration rate, solar radiation shading rate, and inlet and outlet air temperatures at the outdoor unit of an air-conditioner, etc. were measured. Finally the measured data are used to estimate how much energy can be saved by the proposed system.

2. EXPERIMENT

Experimental device and measurement points are shown in Figure 2. Measured items and instruments are shown in Table 1. Data are recorded with five minutes interval using a data logger and sent to authors' office once a day

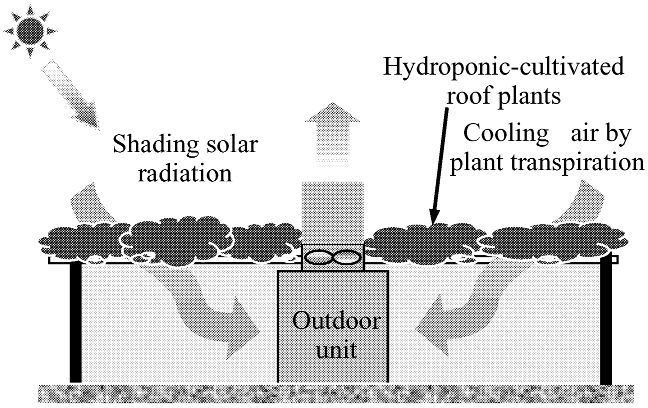

Figure 1. A system combining the hydroponic-cultivated green roof plants with air-conditioners

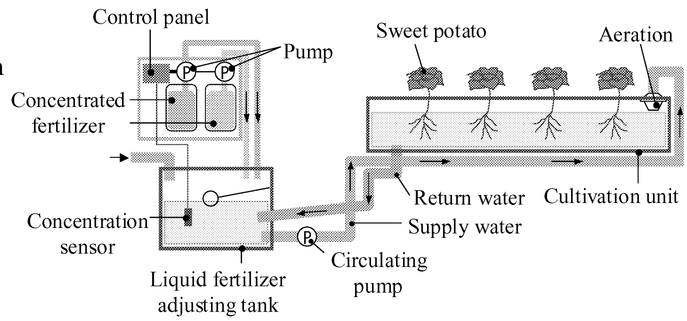

Figure 3. Structure of hydroponic cultivation unit

Table 1. Measured items and instruments

Mark	Item	Point	Instrument
WD	Wind direction	A	vane-type
WS	Wind speed	A	3-cup anemo meter
RU	Solar radiation	B,D	pyranometer
RD	Solar radiation (under green)	2,3	pyranometer
PAR	Photosynthetically active radiation	D	photon sensor
NRF	Net radiation (roof)	C	net radiometer
NRG	Net radiation (green)	4	net radiometer
IR	Infrared radiation	B	infrared radiometer
WF	Water flow	F	flowmeter
TR	Outside air temperature	A	thermohygrometer
HR	Outside air relative humidity	A	thermohygrometer
TU	Temperature (over green)	1～8	thermocouple thermo recorder
HU	Ralative humidity (over green)	1～8	thermo recorder
TD	Temperature (under green)	1～8	thermocouple thermo recorder
HD	Ralative humidity (under green)	1～8	thermo recorder
TDU	Temperature (in duct)	▲	thermocouple
TL	Leaf temperature	1～4	thermocouple
TW	Wall temperature	×	thermocouple
TF	Floor temperature	×	thermocouple
TH	Temperature of suction opening	○	thermocouple
THO	Temperature of supply opening	●	thermocouple

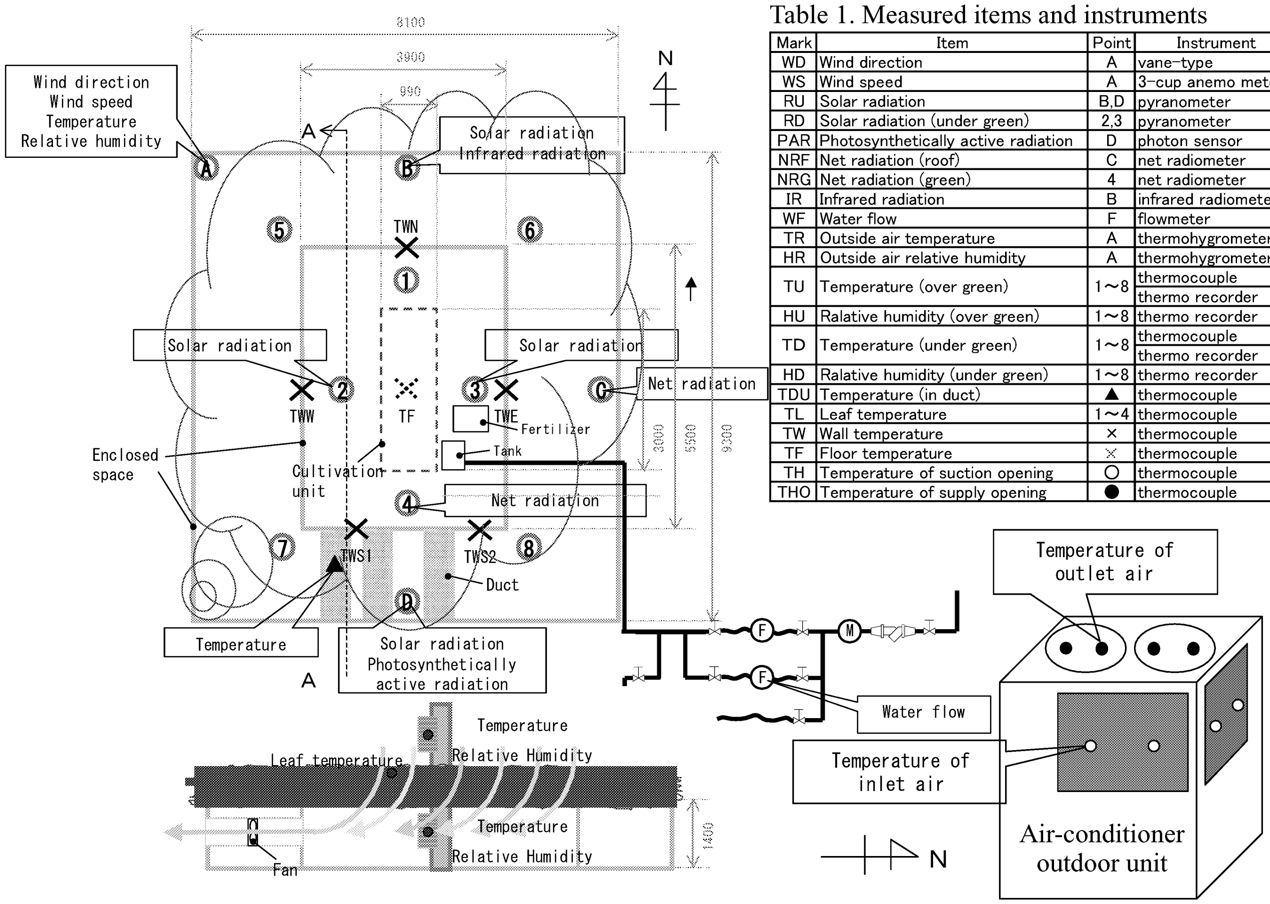

Figure 2. Experimental device and measurement items

through Internet. Experimental device consists of a hydroponic cultivation device, a stage, and three fans. The hydroponic cultivation device consists of two fertilizer tanks, a fertilizing controller, a fertilizer adjustment tank, a circulation pump, and a cultivation unit (Fig. 3). The hydroponic cultivation device is set on a stage of 1.4 meters over the roof. The vertical walls of the stage are closed using isolation material to let air can only flow from upside through the plants. The upper side of the stage is covered by grating, where plants grow and air can flow through. Three ducts equipped with a fan respectively are connected to the south wall of the stage to suck air in the stage acting as the same function of the outdoor unit fans of air-conditioners.

Sweat potato was selected as green roof plant because it has high transpiration rate, grows fast, and is strong against wind. The sweet potato was planted on 22nd May 2007. One month later, it began to grow fast with a speed of 0.8 m^2 of horizontal projection area per day until the end of September. In October, its growth slowed down and withered at the beginning of November. So generally speaking, the air-cooling and solar shading effect can be utilized for two months of August and September, the heavy cooling load period. This indicates that the proposed system is meaningful for actual application.

For the purpose of check the cooling potential of the plants, the following experiments are conducted.

- Set the flow rate of air flowing through the plants at 2000 m^3/h, 4000 m^3/h, and 6000 m^3/h, to check the relations between temperature decrease and air flow rate.
- Sprinkle water up and under the plants to check how much the air-cooling effect can be improved, focusing on cooling air temperature down to wet-bulb temperature. Considering it might damage the plants growth, the water sprinkling experiments are conducted twice a day on 11:00 – 12:00 and 14:00 – 15:00.

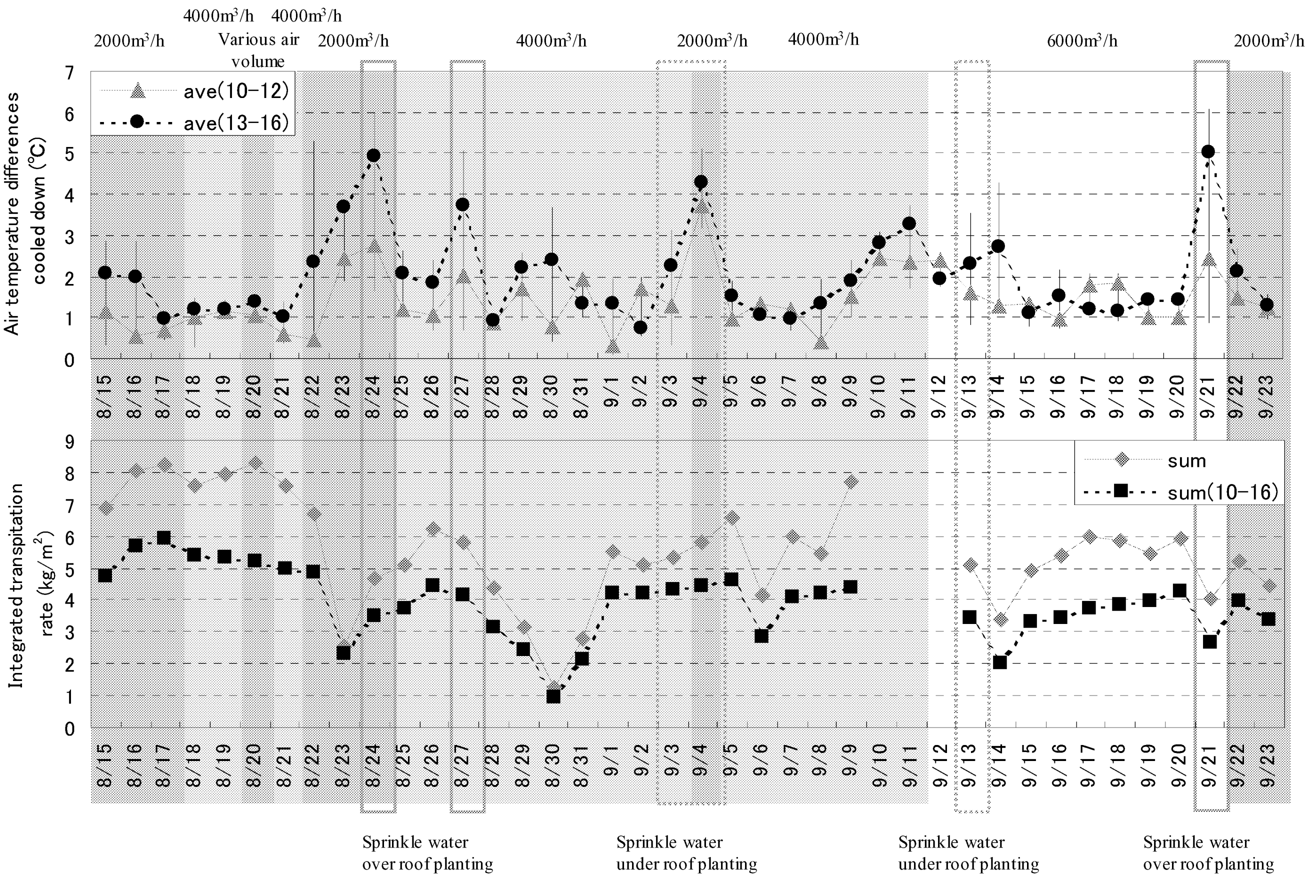

Figure 4. Experimental results of air temperature decrease (upper graph) and transpiration rate (lower graph)

3. EXPERIMENTAL RESULTS

The experimental period are from August 15th to September 23rd. Although data are recorded 24 hours a day, the cooling affect can only be observed during the period when photosynthetic radiation is active enough to trigger plant transpiration. The observed transpiration and cooling effect are mainly in the period of 10:00 – 16:00, therefore the data during this time are used for analysis

3.1 Air temperature decrease

For the experimental period, the daily temperature decreases of maximum, minimum, average of 10:00 – 12:00, and average of 13:00 – 16:00 are as shown in the upper part of Figure 4. The daily average temperature decrease for clear and no-water-sprinkle days is 1.3 ^oC. While the average temperature decrease for rainy or water-sprinkle days is 3.0 ^oC, which is 2.3 times of that in clear and no-water-sprinkle day. However, the temperature decrease does not differ much for the air flow rate of 2000, 4000, and 6000 m^3/h.

3.2 Plants transpiration

The daily sum and 10:00 – 16:00 sum of transpired water are shown in the lower part of the Figure 4. The maximum and average daily summed transpirations are 8.3 and 6.3 kg/m^2 horizontal area respectively for clear and no-water-sprinkle days. For the days when water was sprinkled upon the plants, the transpiration is relatively small because leaves were wet and the transpiration temporally stopped.

The maximum daily transpiration rate (kilogram water per square meter of horizontal projection area) of hydroponoic-cultivate sweat potato is 13.8 times of sedum green roof without water-sprinkle and 1.8 times of sedum green roof with water-sprinkle. The maximum transpiration is similar to a single tree, which indicates the hydroponoic-cultivate sweat potato can transpire as much water as a tree, which has 20 times more leaf volume per unit horizontal projection area than sweat potato.

3.3 Solar radiation shading

The solar radiations up and under the plants on a typical day are shown in Figure 6. Even the solar radiation is as high as 1000 w/m^2, the measured solar radiation under the plants is no more than 10 W/m^2. That is to say more than 99% solar radiation is shaded by the plants. Therefore hydroponic-cultivated green roof can shade solar radiation enough to ignore the influence of solar radiation to the outdoor unit of an air-conditioner.

4. ESTIMATION OF ENERGY SAVING

The calculation flow for estimating the energy saving achieved by the proposed system is shown in Figure 7. Firstly calculate the air cooling effect ΔT caused by plants transpiration and solar shading. Then calculate air-conditioners' energy consumption using an air-conditioner energy consumption model.

4.1 Air cooling effect

The air cooling is caused by two reasons. The first is the plants transpiration. The measured temperature differences between the air up and under the plants are used for the calculation.

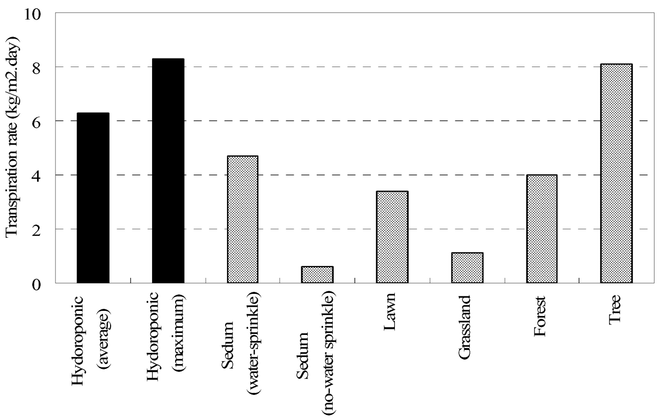

Figure 5. Transpiration comparison

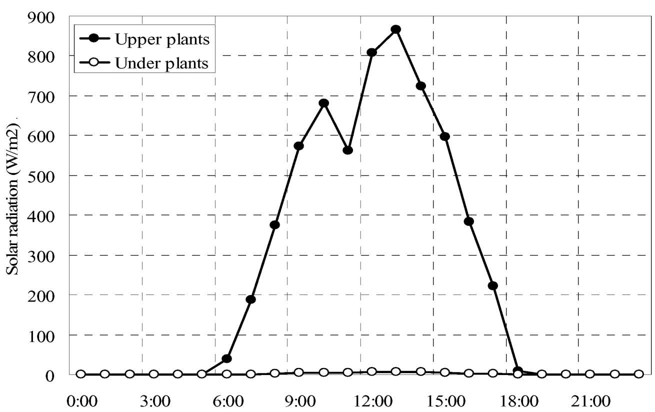

Figure 6. Solar radiation up and under plants

The second is the equivalent air temperature decrease caused by solar shading. If there is no solar shading, the outdoor unit will absorb solar radiation and its surface temperature will rise. This part of heat will raise the temperature of the air sucked into the outdoor unit. The higher the air temperature is, the lower air-conditioners' efficiency will be. The air temperature increase is calculated using the following equations.

$$\Delta T_s = \frac{q_L + \alpha_S q_S}{mC_P} \quad (1)$$

Where:

C_P: Air specific heat (J/kg.^{o}C)

m : Outdoor unit fan air mass flow rate (kg/s)

q_L: Long wave radiation between outdoor unit and its surroundings (W)

q_s : Short wave radiation (i.e. global solar radiation) (W)

α_s: Short wave radiation absorption ratio of outdoor unit surface

ΔT_s: Air temperature increase caused by solar radiation absorption (^{o}C)

4.2 Air-conditioner energy consumption model

A regression model fitted using air-conditioner manufacturer's specification data is used to calculate the air-conditioner's energy consumption (Wang et al., 2005).

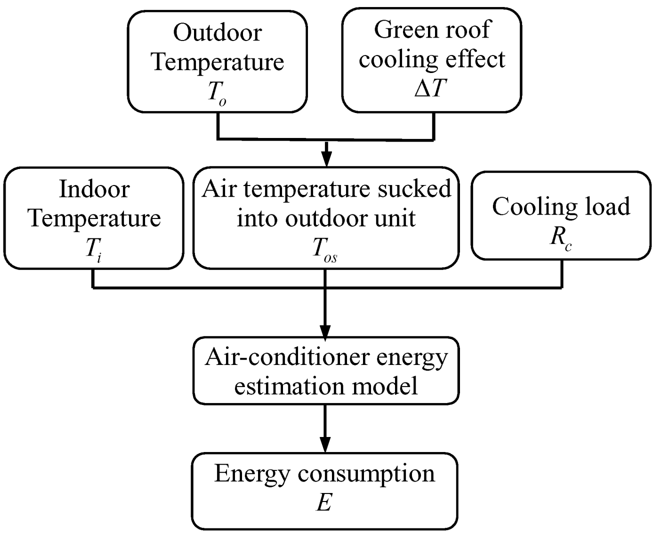

Figure 7. Calculation flow for energy consumption of air-conditioners

$$RE = (a_1 T_{os}^2 + b_1 T_{os} + c_1)(a_2 T_i^2 + b_2 T_i + c_2)(a_3 CA^2 + b_3 CA + c_3) + d \quad (2)$$

$$T_{os} = T_o - (\Delta T_t + \Delta T_s) \quad (3)$$

Where:

a_i, b_i, c_i, d, $i=1,2,3$: Coefficients fitted using manufacturer specification data

CA: Cooling amount produced by an air-conditioner (kW)

T_i: Indoor air wet-bulb temperature (^{o}C)

T_o: Outdoor air dry-bulb temperature (^{o}C)

T_{os}: Dry-bulb temperature of the air sucked into outdoor unit (^{o}C)

ΔT_t: Air temperature decrease caused by plants transpiration (^{o}C)

ΔT_s: Air temperature decrease caused by plants solar shading (^{o}C)

The energy saving is calculated for the typical air-conditioners made by four different manufactures. The average nominal primary energy COP of 1.4 and manufacture year is 2005. Different manufacture's air-conditioners have different efficiency improvement ratio accompanying to outdoor temperature decreasing. So the energy saving is different. The daily average energy savings are shown in Figure 8. The maximum energy saving rate is 12% for the air-conditioners with high efficiency improvement ratio, and 3% for the air-conditioners whose efficiencies improve little accompanying to outdoor air temperature decreasing.

The summed energy savings for the experimental period are shown in Table 2. If water-sprinkle is not conducted, the energy saving ratio is 4% for the product with high efficiency improvement ratio, and 1% for the product with low efficiency improvement ratio. If water-sprinkle is conducted for two hours a day, the energy saving ratios are 9% and 2% for the air-conditioners with high and low efficiency improvement ratio respectively. Among the total energy saving, about 10% is from solar shading 90% is from transpiration.

5. CONCLUSIONS

A system is proposed to utilize hydroponic-cultivated green roof to improve energy efficiency of air-conditioners. Experimental device are set up to check the performance of the proposed system. The experimental results are: 1) The measurement results show that the air temperature differences cooled down by the hydroponic-cultivated sweat potato are 1.3^{o}C in average for clear day and 3^{o}C in average when water was sprinkled; 2) For clear days, the energy saving ratio is about 4% for air-conditioners with high efficiency improvement ratio and 1% for air-conditioners with low efficiency improvement ratio. If water-sprinkle is conducted two hours per day, the energy savings are 9% and 2% respectively.

REFERENCES

Alexandria Eleftheria, Jones Phil (2008), Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates, Building and Environment, Vol. 43, pp. 480–493

Clerk Corrie, Adriaens Peter, Nriantalbot Albot, Talbot F. Brian (2008), Green Roof Valuation: A Probabilistic Economic Analysis of Environmental Benefits, Environmental Science Technology, Vol. 42, pp. 2155–2161

Di H. F. and Wang D. N. (1999), Cooling Effect of Ivy on a Wall, Experimental Heat Transfer, Vol. 12, pp.235-245

Elena Palomo Del Barrio (1998), Analysis of the green roofs cooling potential in buildings, Energy and Buildings, Vol. 27, pp.179-193

Kumar Rakesh, Kaushik S.C. (2005), Performance evaluation of green roof and shading for thermal protection of buildings Building and Environment, Vol. 40, pp. 1505–1511

Spala A., Bagiorgas H.S., Assimakopoulos M.N., Kalavrouziotis J., Matthopoulos D., Mihalakakou G. (2008), On the green roof system. Selection, state of the art and energy potential investigation of a system installed in an office building in Athens, Greece, Renewable Energy, Vol. 33, pp.173-177

Takebayashi Hideki, Moriyama Masakazu (2007), Surface heat budget on green roof and high reflection roof for mitigation of urban heat island, Building and Environment, Vol. 42, PP. 2971–2979

Wang Fulin, Yoshida Harunori, Masuhara Satoshi, Kitagawa Hiroaki, and Goto Kyoko (2005), Simulation-Based Automated Commissioning Method for Air-Conditioning Systems and Its Application Case Study, Proceedings of the 9th International Building Performance Simulation Association Conference, Montreal, Canada, pp. 1307-1314

Wong Nyuk Hien, Chen Yu, Ong Chui Leng, Sia Angelia (2003) Investigation of thermal benefits of rooftop garden in the tropical environment, Building and Environment, Vol. 38, pp.261-270

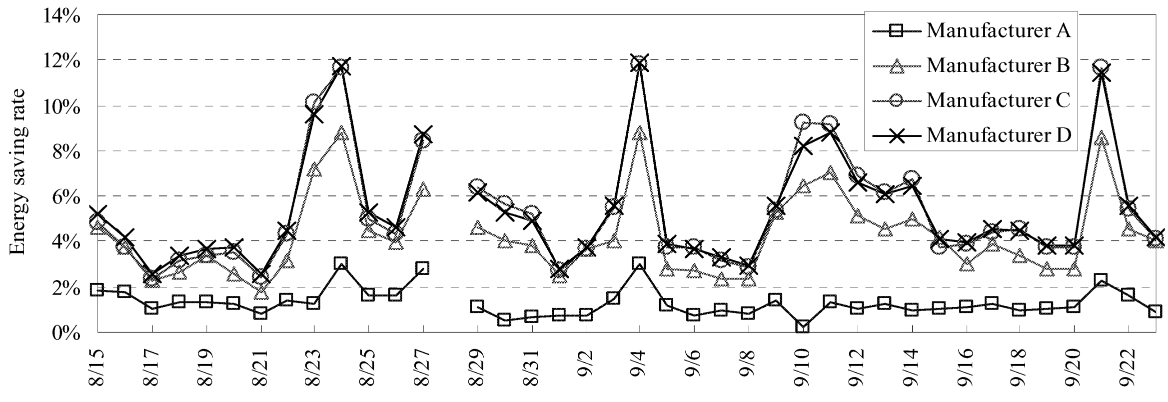

Figure 8. Daily average energy saving rate achieved by using hydroponic-cultivated sweat potato

Table 2. Summed Energy saving achieved by hydroponic-cultivated sweat potato

	Group 1			Group 2			Group 3					
	Manufacturer A (GHP)			Manufacturer B (EHP)			Manufacturer C (GHP)			Manufacturer D (EHP)		
	Energy consumption		Energy saving rate	Energy consumption		Energy saving rate	Energy consumption		Energy saving rate	Energy consumption		Energy saving rate
With or without green roo	With	Without		With	Without		With	Without		With	Without	
sum of Clear and no-water-sprinkle days	2830.5	2859.7	1.0%	2376.4	2449.9	3.0%	2673.1	2767.7	3.4%	2227.6	2317.9	3.9%
sum ofwater-sprinkle days	1024.9	1046.7	2.1%	905.4	970.9	6.7%	965.5	1050.3	8.1%	875.2	963.8	9.2%
sum of rainy days	1011.5	1019.6	0.8%	766.0	810.7	5.5%	857.5	917.6	6.5%	703.4	758.4	7.2%