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Takebayashi, Hideki

Moriyama, Masakazu

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Surface Heat Budget on Green Roof and High Reflection Roof for Mitigation of Urban Heat Island

Hideki Takebayashi (Research associate, Department of architecture and civil engineering, Faculty of engineering, Kobe university)
Masakazu Moriyama (Professor, Department of architecture and civil engineering, Faculty of engineering, Kobe university)

Abstract

In this study, the surface temperature, net radiation, water content ratio, etc., of green roofs and high reflection roofs are observed. The heat and water budget are compared to each other. In the daytime, the temperature of the cement concrete surface, the surface with highly reflective gray paint, bare soil surface, green surface, the surface with highly reflective white paint are observed to be in descending order. On a surface with highly reflective white paint, the sensible heat flux is small because of the low net radiation due to high solar reflectance. On the green surface, the sensible heat flux is small because of the large latent heat flux by evaporation, although the net radiation is large. On the cement concrete surface and the surface with a highly reflective gray paint, the sensible heat fluxes have almost the same values because their solar reflectance is approximately equal. These tendencies of the sensible heat flux accord with the pitch relation of the surface temperature. Methods to estimate the quantity of evaporation, evaporative efficiency, heat conductivity, and thermal capacity are explained, and the observation data is applied to these methods.

Key words: Urban heat island, Surface heat budget, Green roof, High reflection roof

1. Introduction

Improvement in the surface cover of buildings and constructions that have been covered with cement and asphalt concrete is examined as one of the measures to mitigate the urban heat island phenomenon. Green roofs, high reflection roofs, wall planting, etc., are suggested from the viewpoint of building planning, and green parks, roadside trees, etc., are suggested from the viewpoint of urban planning.

The use of highly reflective paint for cool roofs and road pavements is examined by Akbari et al., (2005, 2001, 1999, 1988) from the heat island group of the Lawrence Berkeley National Laboratory for reducing urban heat islands and energy consumption. According to their test calculation, the possibility of reduction or savings in the annual air conditioning costs was estimated to be 35 million dollars in Los Angeles, 16 million dollars in New York, and 10 million dollars in Chicago.

At the Lawrence Berkeley National Laboratory and the Oak Ridge National Laboratory, the database of the characteristics of the roof materials (reflectivity and emissivity) available in the market is prepared and new products are developed.

The purpose of this study is as follows.

1) From the viewpoint of urban heat island mitigation, the sensible heat flux reduction for the roof surface serves as the evaluation index. therefore, the surface heat budgets on some roof covers are examined under the same weather condition. Consequently, the sensible heat flux from the surface to air is compared from the heat island mitigation effect.

2) The estimation method of the sensible heat flux from each roof surface is investigated. The heat budget components are derived from the observation results. Finally, the sensible heat flux from each roof surface is estimated by the residue of the surface heat budget.

2. Outline of observation

The observation period is from July, 2003, to the present. It is carried out on the experimental roof of the 8-story building of the Kobe University. In this study, the observation data for August and November 2004 is used for the detailed discussion. Unit numbers 1, 2, 9, 11, and 12 in figure 1 are used for the detailed discussion. The unit size for the bare soil surface (unit number 1) is 1.175m * 1.6 m; for the green (lawn) surface (unit number 2), 0.95m * 1.6m; and for the paint and cement concrete surfaces (unit numbers 9, 11, and 12), 0.942m * 1.0m. A summary of the observation unit is shown in table 1.

Air temperature, relative humidity, solar radiation, infrared radiation, precipitation, wind direction, and velocity, are observed as weather conditions near the observation site. In each observation unit, downward and upward, and short wave and long wave radiation (net radiation); surface temperature; internal temperature; and heat flux are observed. The water content ratio in the soil under the green surface and bare soil is observed. The observation points of temperature, heat flux, and water content ratio are shown in figure 2. The heat flux sensor and thermo-couple are installed in the concrete slab of each unit. In addition, the air temperature in the room under the slab is controlled by an air conditioner.

3. Observation result

3.1 Observation result of the surface temperature

Weather condition in August and November 2004 are shown in figures 3 and 4. Observation results of the surface temperature in August and November 2004 are shown in figures 5 and 6. Although the leaf surfaces and the region around the roots in a lawn are expected to have difference temperatures, only the result of the leaf surface temperature is shown, which is observed continually by a radiation thermometer.

In August, the surface temperature of the (cement) concrete slab and the highly reflective gray paint is almost the same and higher by about 10 degrees than that on surfaces with highly reflective white and green paints. The surface temperature on the green surface is several degrees lower than that on bare soil, and it is several degrees higher than that on the highly reflective white paint.

However, in November, the surface temperature on the green surface and bare soil are approximately the same. It is considered that due to evapotranspiration, the surface temperature on the green surface in summer is lower.

3.2 Observation result for net radiation

Solar reflectance is estimated from the observation result in each observation unit by the net radiation sensor. Each unit is not sufficiently large; therefore, the influence by reflection from the circumference is included in the observation result. To eliminate this influence, a revision calculation is performed by using simultaneous equations, which are considered to mutually influence each other's aspects, and employing the form coefficient at the establishment height. The revision calculation is expressed in the following expressions.

$$\rho_{obs} = \frac{S\uparrow_{obs}}{S\downarrow_{obs}} \tag{1}$$

$$\begin{bmatrix} \phi_{11} & \cdots & \phi_{1n} \\ \vdots & \ddots & \vdots \\ \phi_{n1} & \cdots & \phi_{nn} \end{bmatrix} \begin{bmatrix} \rho_1 \\ \vdots \\ \rho_n \end{bmatrix} = \begin{bmatrix} \rho_{1obs} \\ \vdots \\ \rho_{nobs} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} \rho_1 \\ \vdots \\ \rho_n \end{bmatrix} = \begin{bmatrix} \phi_{11} & \cdots & \phi_{1n} \\ \vdots & \ddots & \vdots \\ \phi_{n1} & \cdots & \phi_{nn} \end{bmatrix}^{-1} \begin{bmatrix} \rho_{1obs} \\ \vdots \\ \rho_{nobs} \end{bmatrix} \tag{3}$$

Here, ρ_{obs} : Observed solar reflectance, ρ : Revised solar reflectance, $S\downarrow_{obs}$: Observed solar radiation (W/m^2), $S\uparrow_{obs}$: Observed reflective solar radiation (W/m^2), ϕ : Form coefficient at the establishment height, n: Each observation unit. The solar reflectance on each observation unit is shown in table 2.

In the visible wave length, the spectral reflectance of the highly reflective gray paint is the same as that of the general gray paint. In the infrared wave length, the spectral reflectance of the highly reflective gray paint is larger than that of the general gray paint. Therefore, in the total wave length, the reflectance of highly reflective gray paint is larger than that of the general gray paint, although they have the same appearance.

3.3 Observation result of water content ratio

Observation results of the water content ratio, which is observed by TDR sensors, are shown in figures 7 and 8. Six TDR sensors are set in the soil under the green surface, and three TDR sensors are set in the bare soil. Data for the sensors under the green surface are obtained in August and November, and that for the sensors under bare soil are obtained in November.

The dielectric constant in the soil is estimated from the time when an electromagnetic wave travels between two probes buried in the soil, and the water content ratio is calculated from a recurrence equation that was prepared beforehand. Probes are connected to a data logger, and the data is automatically recorded in the same manner as that for temperature and heat flux. Therefore, this method is advantageous in that it can be applied more easily to the actual building than the method of regular soil weight measurement.

From the observation results, the water content ratio is the highest in the deepest layer, both in August and November, and the decrease ratio in the water content ratio with the passage of time is the largest in the deepest layer. It is considered that the water moves from the lower part to the surface. Therefore, when examining the characteristic of the quantity of evaporation, it is necessary to consider water movement from the lower layer to the upper layer as well as the surface characteristics of the neighboring regions.

3.4 Estimation of quantity of evaporation

The quantity of evaporation is estimated from the observation result of the water content ratio in the green surface and the bare soil surface. The quantity of evaporation is expressed as the quantity that is obtained by deducting the increase in the water content in the total soil layer and drainage from precipitation (sprinkling); it is supposed that evaporation occurs only at the green and bare soil surfaces. The water content of each layer is obtained by multiplying the density of water and the volume of each layer with the water content ratio. The water content in the total soil layer is integrated by multiplying the water content of each layer with the total soil depth.

The estimation results of the quantity of evaporation from the green surface and the bare soil surface in August and November are shown in figures 9 and 10. The quantity of evaporation from the green surface in November is almost half of that in August. The difference in the quantity between night and day is larger in August and that in November is low.

From the estimation results in November, the quantity of evaporation from the bare soil surface is found to be larger than that from the green surface; it is considered that evaporation, which occurs suddenly, is prevented by the lawn, which moderates the influence from the atmosphere such as wind velocity.

The quantity of evaporation from the green surface is larger than that from the bare soil surface in the night. In reality, it is considered that the quantity of evaporation in the night is very small; however, it is estimated that evaporation occurs in the night since the soil and the green surface draws up water from the deeper layer to the upper layer. This is because in this estimation method, the water accumulated in the soil and the lawn around the surface is not considered to be sufficient. This aspect is considered to be a problem of this estimation method.

4. Calculation method of the heat and water budget

4.1 Surface heat budget

The surface heat budget is expressed as follows: It is supposed that evaporation is only carried out at the surface.

$$Rn = A + V + lE \tag{4}$$

$$A = -\lambda \left.\frac{\partial T}{\partial z}\right|_{z=0} \tag{5}$$

$$V = \alpha (Ts - Ta) \tag{6}$$

$$lE = l \cdot \beta \cdot \alpha_w (Xs - Xa) = l \cdot \beta \cdot \alpha / Cp \cdot (Xs - Xa) \tag{7}$$

Here, Rn: Net radiation (W/m^2), A: Conduction heat flux (W/m^2), V: Sensible heat flux

(W/m^2), lE: Latent heat flux (W/m^2), λ: Heat conductivity (W/mK), α: Convective heat transfer coefficient (W/m^{2}K), Ts: Surface temperature (C), Ta: Air temperature (C), β: Evaporative efficiency (-), Cp: Specific heat of air (J/kgK), Xs: Saturated humidity (kg/kg), Xa: Air absolute humidity (kg/kg).

The outline of the heat budget analysis is shown in figure 11. The numbers in the parenthesis of this figure show the passage in which the parameter is discussed.

4.2 Equation of heat conduction and water movement

Expressions on heat conduction and water movement in the soil are expressed below. It is supposed that evaporation occurs only at the soil surface and water movement in the soil is the only transportation of liquid water.

$$\left.\frac{\partial \theta}{\partial t}\right|_m = D_\theta \frac{\partial \theta^2}{\partial z^2} + D_T \frac{\partial T^2}{\partial z^2} + \frac{\partial K}{\partial z} \quad (8)$$

$$\left.\frac{\partial T}{\partial t}\right|_m = \frac{\lambda}{c}\frac{\partial T^2}{\partial z^2} \quad (9)$$

Here, θ: Water content ratio (m^3/m^3), K: Hydraulic conductivity (m/s), D_θ, D_T: Molecule diffusion coefficients of liquid water; D_θ (m^2/s) and D_T (m^2/sK) are functions of K and the capillary potential, Ψ(θ) and Ψ(T) (m), respectively, and c: Thermal capacity (J/m^{3}K), $c = C_{p_s} \times \gamma_s$; C_{ps}: Specific heat of the soil (J/kgK), γ_s: Density of the soil (kg/m^3).

Six TDR sensors are set in the soil under the green surface, and three TDR sensors are set in the bare soil in this study; however, it is considered that the same result as this observation result is obtained by a few more observing instruments if boundary conditions and data on the soil material properties exist.

4.3 Estimation of heat conductivity and thermal capacity

Heat conductivity λ and thermal capacity c are estimated from the observation results. When equations (5) and (9) are differentiated, they are expressed as follows:

$$A = -\lambda \frac{\Delta T}{\Delta z} = \frac{\lambda}{\Delta z}(T_s - T_1) \tag{10}$$

$$\lambda \frac{1}{\frac{\Delta z_1}{2} + \frac{\Delta z_2}{2}} \left(\frac{T_{m-1} - T_m}{\Delta z_1} - \frac{T_m - T_{m+1}}{\Delta z_2}\right) = c \frac{(T_m - T_m^{*})}{\Delta t} \tag{11}$$

Here, Δz: Distance between T_s and T_1 (m), Δz_1: Distance between T_{m-1} and T_m (m), and Δz_2: Distance between T_m and T_{m+1} (m). Observation values of temperature and conduction heat flux are substituted for these expressions.

The vertical axis of figure 12 is the conduction heat flux A, the cross axle is the value that divides the temperature difference between the upper and lower part of the heat flux sensor by the distance. It is considered that the degree of the approximation straight line is heat conductivity λ. In addition, when the heat conductivity λ that is obtained from figure 12 is substituted for equation (8), the thermal capacity c is estimated. The estimation result of the thermal capacity c of the concrete slab is shown in figure 13. It is considered that the degree of the approximation straight line is the thermal capacity c.

The heat conductivity and thermal capacity of soil are estimated by the same methods, but they change by the water content ratio θ (m^3/m^3). The following function by water content ratio is used for the estimation:

$$\lambda = 0.025 + 0.5\theta^{1/3}, \quad c(\theta) = (1 - \theta_{SAT})c_{SOIL} + \theta c_{WATER}$$

Here, θ_{SAT}: Saturated water content ratio (m^3/m^3), c_{soil}: Thermal capacity of soil (J/m^3K), and c_{water}: Thermal capacity of water (J/m^3K).

4.4 Estimation of evaporative efficiency

The evaporative efficiency β is necessary to find the quantity of evaporation from equation (7). At first, the initial evaporative efficiency β is substituted, and the quantity of evaporation is calculated by equation (7). It is compared with the estimation result of the quantity of evaporation obtained in 3.4; the suitable value for evaporative efficiency β is obtained by repeating this step. In reality, the evaporative efficiency β changes with the time; however, it is supposed that the evaporative efficiency β is constant in the period under consideration because when the water content condition of the soil does not change greatly, it is considered that the evaporation efficiency β is constant.

The quantity of evaporation obtained from the observation result of the soil water content ratio appears greater in the night because the water moves from the deeper layer to the surface neighborhood during the night. Therefore, the quantity of evaporation that is multiplied for a certain period is used for the comparison between the observation and calculation values.

When equations (4), (6), and (7) are arranged, the quantity of evaporation is expressed as follows:

$$Rn - A = \alpha\left\{(Ts - Ta) + l \cdot \beta \cdot \frac{1}{Cp}(Xs - Xa)\right\} \tag{12}$$

When Rn and A are given, α and β are the only unknown quantities; if the temporary value is applied to β and α is provided, then the quantity of evaporation is obtained. The period multiplied value of the quantity of evaporation provided by this method is compared with that obtained from the water content ratio observation, and the value when the difference becomes the smallest is determined to be the suitable evaporation ratio β in this period.

The evaporative efficiency β is obtained by the abovementioned method, as shown in figure 14. The cross axis is the evaporative efficiency β and the vertical axis is the difference between the period multiplied value of the quantity of evaporation provided by the calculation and that provided by the water content ratio observation. At the time β = 0.14, this difference becomes the smallest; therefore, this value is used for the following analysis of the surface heat budget on the green surface.

5. Surface heat and water budget

5.1 Calculation of the water content ratio in the soil

Equations (8) and (9) are calculated by the retreat difference method. The comparison between the calculation result and the observation result of the water content ratio in some layers and the quantity of evaporation on November 5–7, 2004 are shown in figures 15 and 16. The quantity of evaporation is calculated by using the calculation result of the water content ratio. The observation values of the water content ratio in the 2-cm and 21-cm layer are used for boundary condition. The parameters for the soil properties are adopted from the reference lists. (e.g., Kondo, J., 1994, 2000)

In the 16-cm layer, the calculation result of the water content ratio is a little higher than the observation result; however, they are approximately the same observation results as in the 6-cm and 11-cm layers. The calculation values of the quantity of evaporation are slightly smaller in comparison with the observation values. Although the water content ratio is supposed to be a uniform value, it is considered that, in reality, the values for each layer in the soil are distributed.

5.2 Calculation of surface heat budget

The calculation result of the surface heat budget on each surface is shown in figures 17–20. The evaporative latent heat flux is estimated by the above method, and the sensible heat flux is calculated by the residue of the surface heat budget. The evaporative efficiency β on the green surface is assumed to be 0.14, and the evaporative latent heat flux on the paint and concrete surface is not considered.

On the surface with the highly reflective white paint, the conduction heat flux and the sensible heat flux are smaller than those on the concrete slab because the quantity of net radiation is small. On the surface with highly reflective gray paint, the conduction heat flux and sensible heat flux are approximately the same as those on the concrete slab.

Although in the daytime net radiation on the green surface is the largest in this study because of the small solar reflectance, the sensible heat flux is small because a large part of the absorbed heat is used for evaporation. The sensible heat flux on the green surface is about 60W/m^2 lower than that on the concrete slab at its maximum, and the difference is also confirmed in the night. The maximum and average sensible heat fluxes on each surface are shown in table 3.

6. Summary

The surface temperature, net radiation, water content ratio, etc., are observed on the green roof and the high reflection roof. Then, the heat and water budget are compared to each other. Summaries of this study are as follows.

1) On the surface with highly reflective white paint, the sensible heat flux is small because of the low net radiation by high solar reflectance. On the green surface, the sensible heat flux is small because of the large latent heat flux by evaporation, although the net radiation is large. On the cement concrete surface and the surface with the highly reflective gray paint, the sensible heat fluxes have almost same values because their solar reflectance is approximately equal. These tendencies of the sensible heat flux accord with the pitch relation of the surface temperature.

2) In heat and water budget analysis, a method to estimate the quantity of evaporation using the observation result of the water content ratio in the soil is applied. In this method, the water content ratio in each layer in the soil is supposed to be uniform; the detailed distribution of water in a particular surface neighborhood is not considered; therefore, this point is considered to be a problem for investigation.

3) Methods to estimate the evaporative efficiency, heat conductivity, and thermal capacity are explained, and the observation data is applied to these methods. The estimation values are compared with the reference values, and the propriety of these methods is confirmed. Then, the estimated values are used for the calculation of the surface heat budget. However, it is necessary to examine the suitability of this method by using various types of data and for longer periods.

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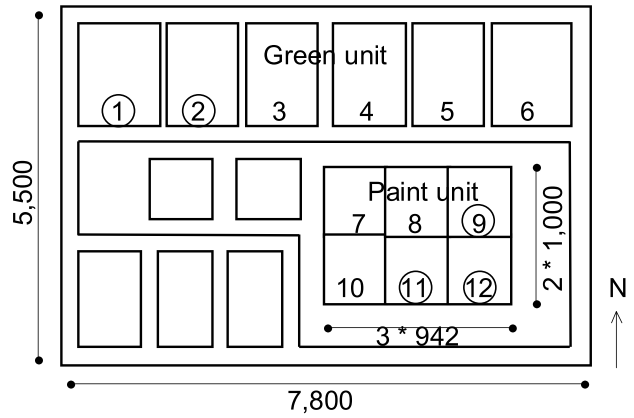

1: Bare soil, 2: Green (lawn-grass), 9: (Cement) Concrete
11: High reflective white paint, 12: High reflective gray paint

Figure 1 Experimental roof plan

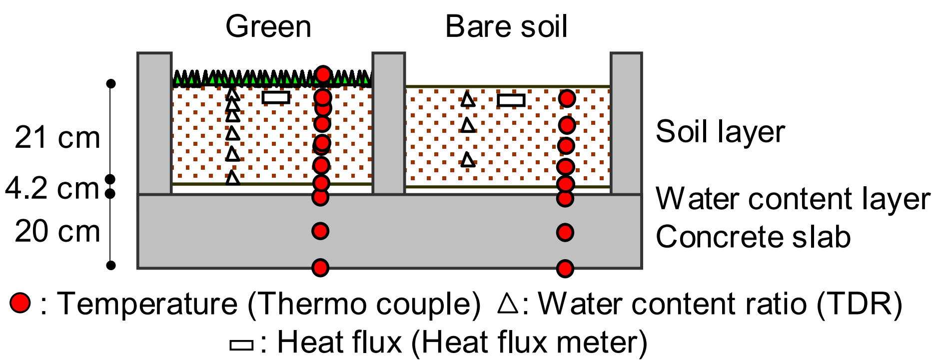

Figure 2 Observation points of temperature, water content ratio, and heat flux

Temperature observation points under the green surface are at 2, 4, 6, 10, 11, 16, and 21 cm from the surface.

Temperature observation point under the bare soil surface is 2, 6, 10, 16, and 21 cm from the surface.

Water content ratio observation point under the green surface is 2, 4, 6, 11, 16, and 20 cm from the surface.

The water content ratio observation point under the bare soil surface is 2, 6, and 16 cm from the surface.

Heat flux observation point under the green and bare soil surface is 2 cm from the surface.

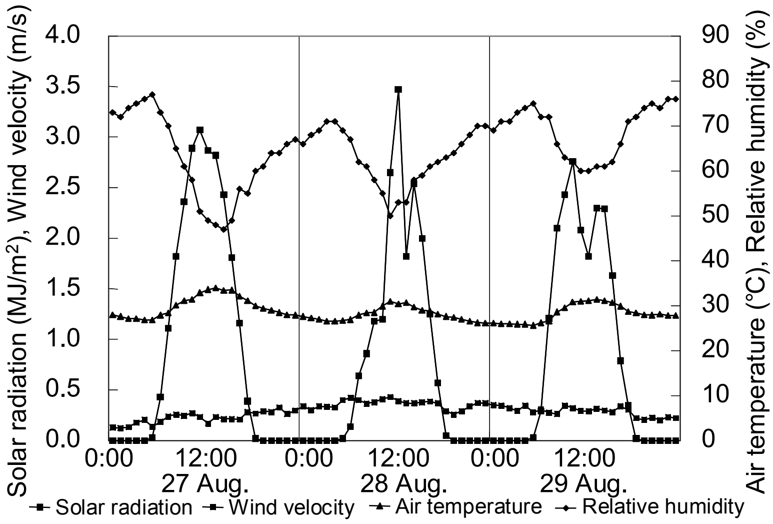

Figure 3 Weather condition on August 27–29, 2004

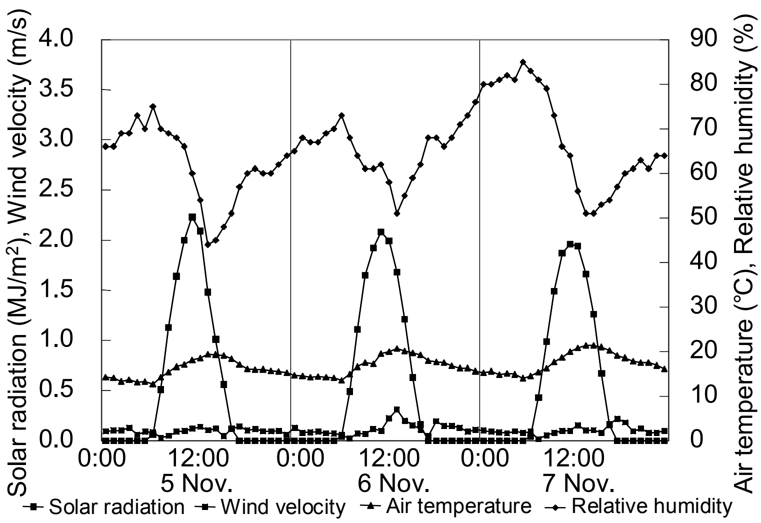

Figure 4 Weather condition on November 5–7, 2004

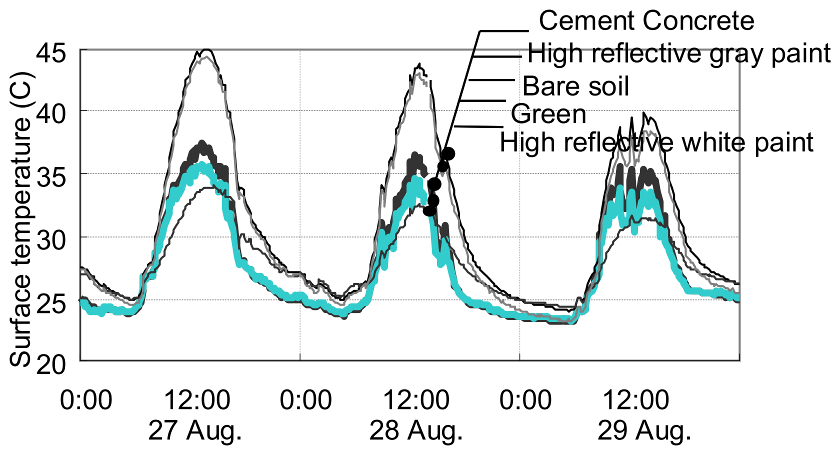

Figure 5 Observation result of the surface temperature on August 27–29, 2004

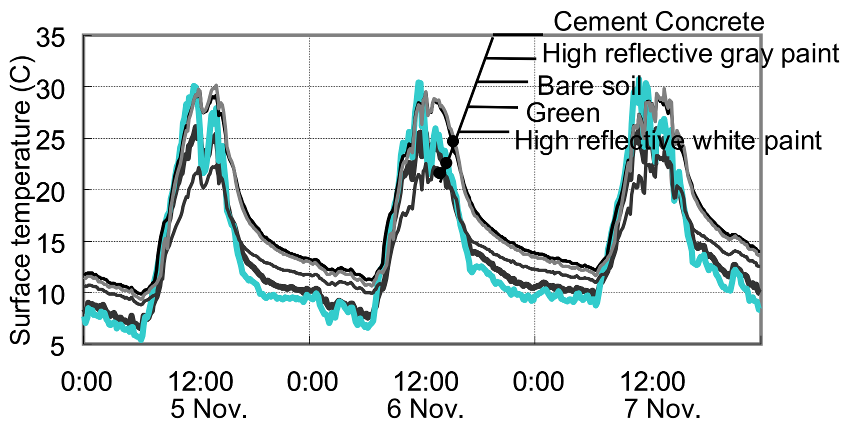

Figure 6 Observation result of the surface temperature on November 5–7, 2004

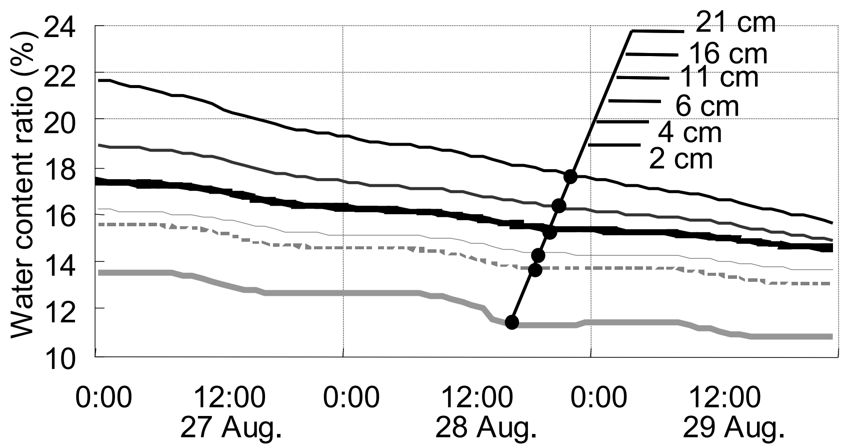

Figure 7 Observation results of the water content ratio under the green surface on August 27–29, 2004

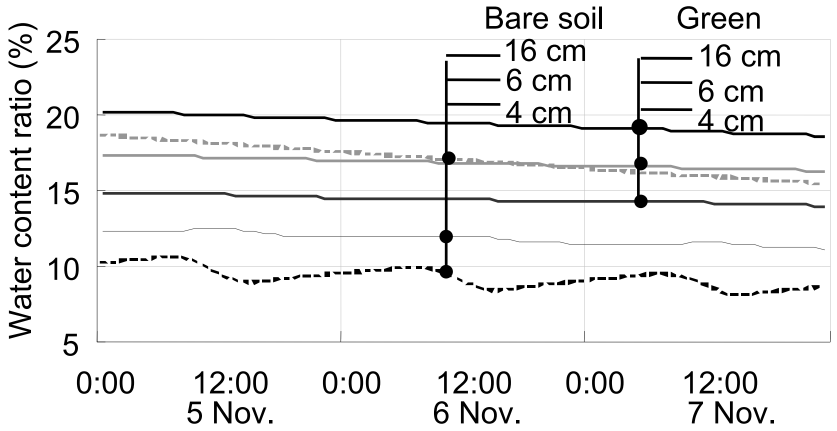

Figure 8 Observation result of the water content ratio under the green surface and bare soil on November 5–7, 2004

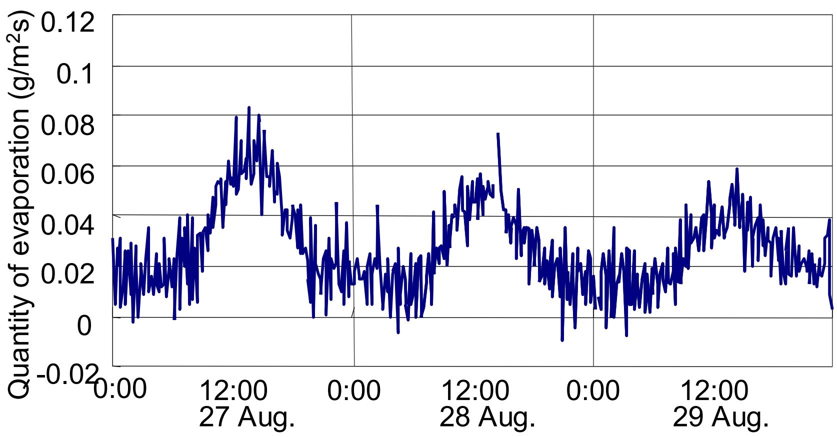

Figure 9 Estimation result of the quantity of evaporation from the green surface on August 27–29, 2004

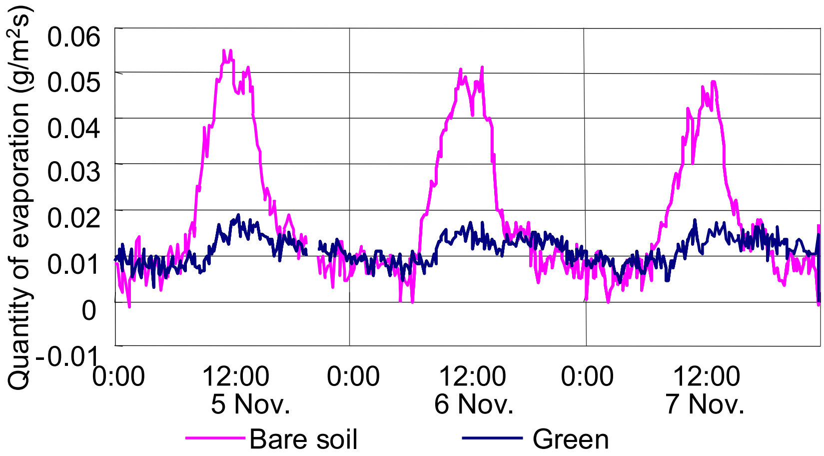

Figure 10 Estimation result of the quantity of evaporation from the green surface and bare soil surface on November 5–7, 2004

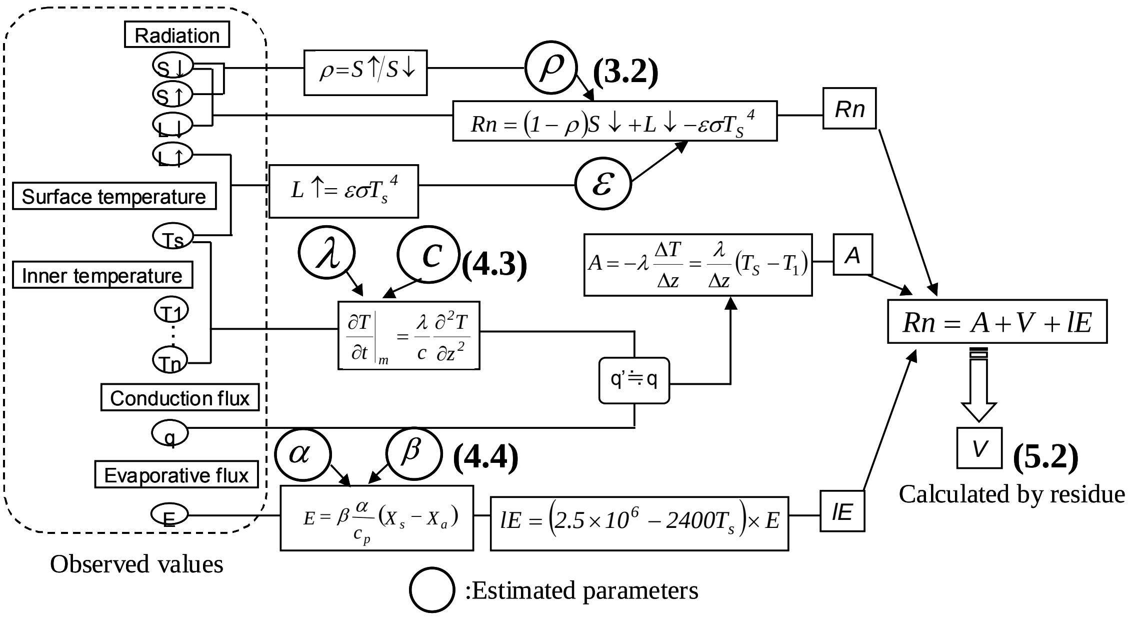

Figure 11 Outline of the heat budget analysis

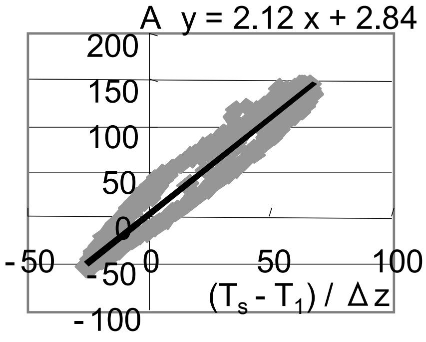

Figure 12 Estimation of heat conductivity λ

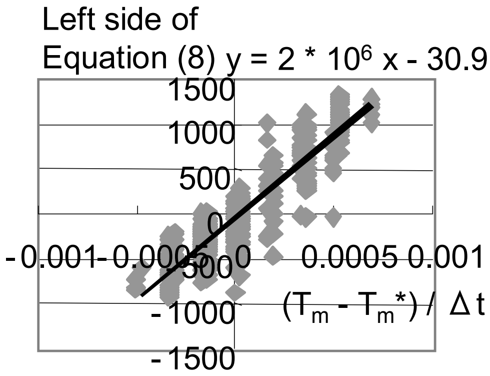

Figure 13 Estimation of thermal capacity c

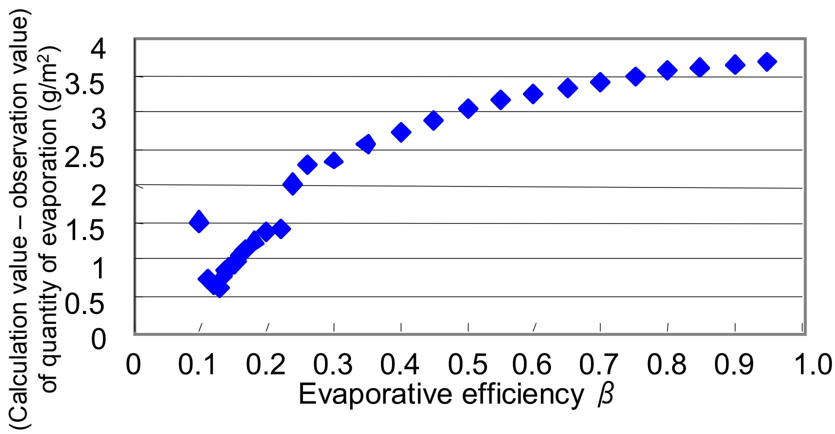

Figure 14 Estimation of evaporative efficiency β

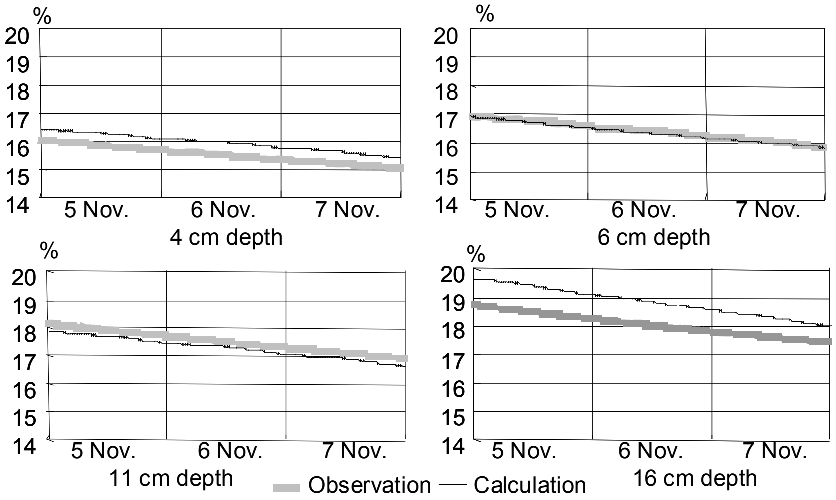

Figure 15 Calculation result and observation result of the water content ratio in some layers on November 5–7, 2004

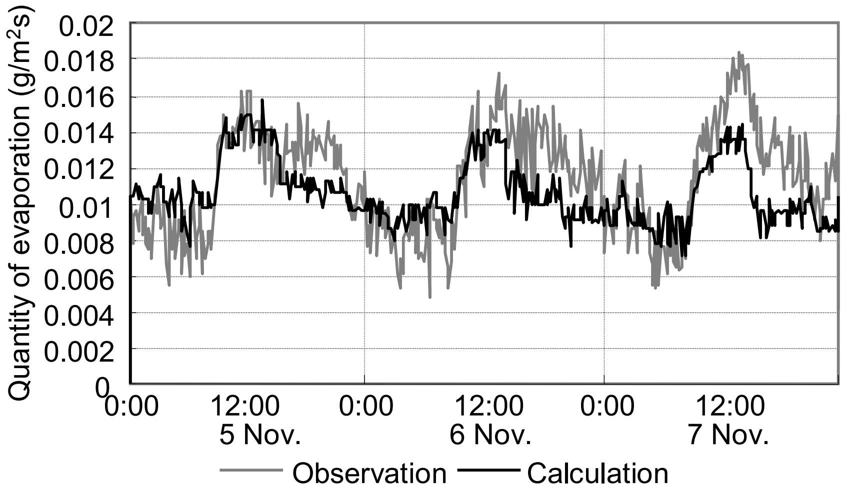

Figure 16 Calculation result and observation result of the quantity of evaporation on November 5–7, 2004

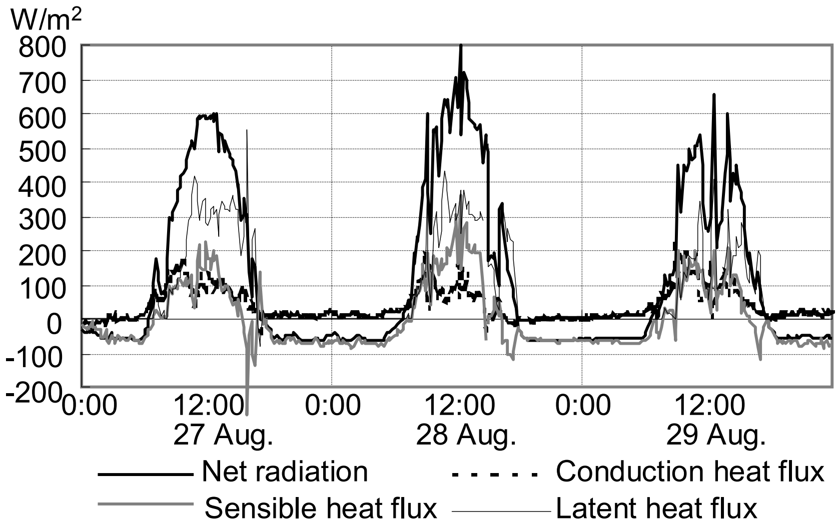

Figure 17 Surface heat budget on the green surface on August 27–29, 2004

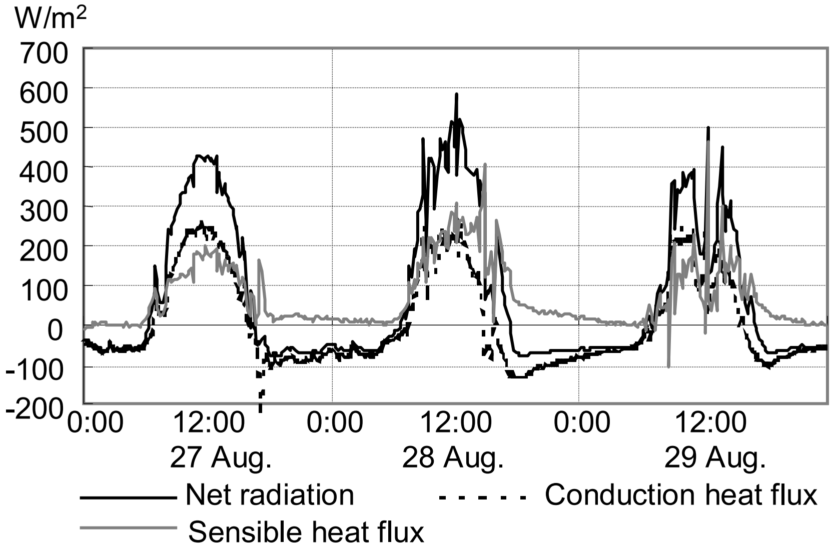

Figure 18 Surface heat budget on the cement concrete surface on August 27–29, 2004

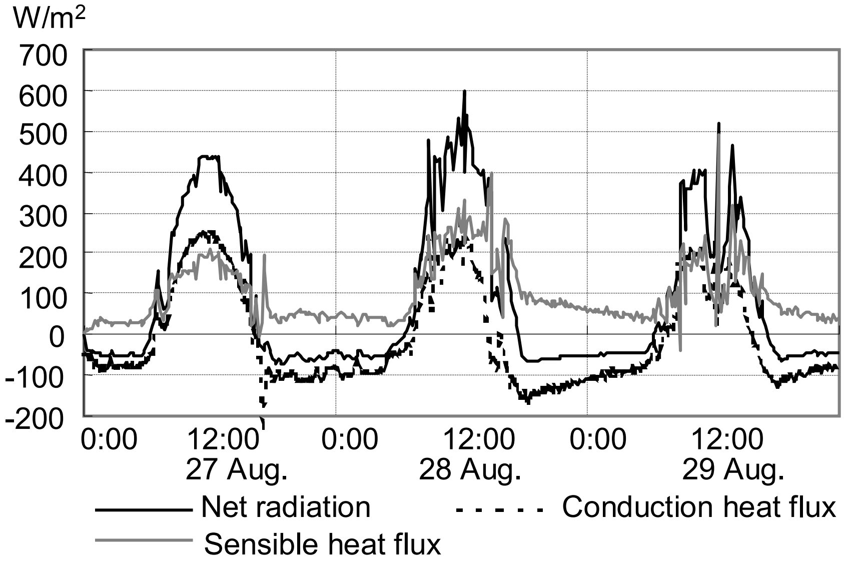

Figure 19 Surface heat budget on the surface with highly reflective gray paint on August 27–29, 2004

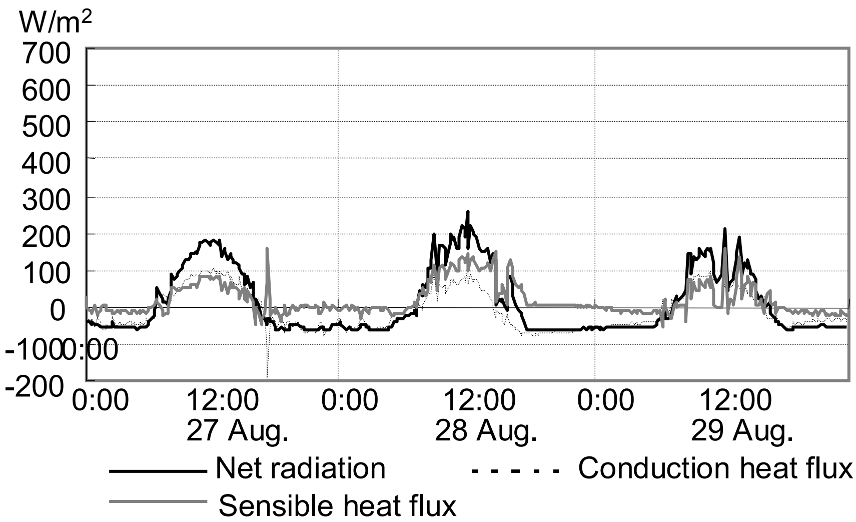

Figure 20 Surface heat budget on the surface with highly reflective white paint on August 27–29, 2004

Table 1 Outline of the experimental roof

Unit Number	Experimental object
1	Bare soil
2	Green (lawn)
9	(Cement) Concrete
11	Highly reflective white paint
12	Highly reflective gray paint

Table 2 Solar reflectance (Albedo) of each surface

Observation Surface	Bare soil	Green	Concrete	Highly reflective gray paint	Highly reflective white paint
Solar reflectance	0.17	0.15	0.37	0.36	0.74

Table 3 Sensible heat flux on each surface (maximum, average on August 27–29, 2004)

W/m^2	Green	Concrete	Highly reflective gray paint	Highly reflective white paint
Maximum	361	408	399	153
Average	2	72	97	20