

Field Measurement on Energy Budget of Isolated Plant Unit

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ABSTRACT

It is necessary to evaluate a green effect quantitatively to promote urban greening. Energy balance of plant is important information for the thermal environment design. In urban space, a lot of isolated plants such as vegetation at individual residences and street trees are seen. However, there are few studies on energy balance of such an isolated plant, and useful data is hard to get. Then, in this study, the energy balance of the isolated plant unit is measured or expected, and the quantitative evaluation has been performed for urban space planning.

Introduction

The thermal environment in urban area keeps deteriorating by the heat island phenomenon that has become aggravated in recent years. To solve such a problem, the role of plant is reviewed. For the quantitative forecast of the climate easing measures of plant, it is important to understand the energy budget of the plant body. Many have been researched so far, and the basic data is being maintained by the technical studies on the energy budget of large-scale forest belt, meadow, and plant community for rooftop gardening (Kanda, et al. 1997 and Misaka, et al. 2007). There are few researches on the energy budget of isolated plant like planting, gardening and street trees in urban space. Then, in the present study, the energy balance of the isolated plant unit is measured in the field, and the quantitative evaluation has been performed for urban space planning.



(a) camphor tree



(b) hibiscus

Figure 1. Isolated tree and potted plant of measured object

Object plants are shown in Figs.1 (a) and (b). The camphor tree is one of the wood species often used in general in Japan as street trees. The hibiscus is popular in Japan as the plant for the garden. The energy budgets of the isolated single tree and the potted plant are shown in the present study. After then, the heat transfer coefficient on leaf side and the evaporation efficiency compared with the water surface are also discussed.

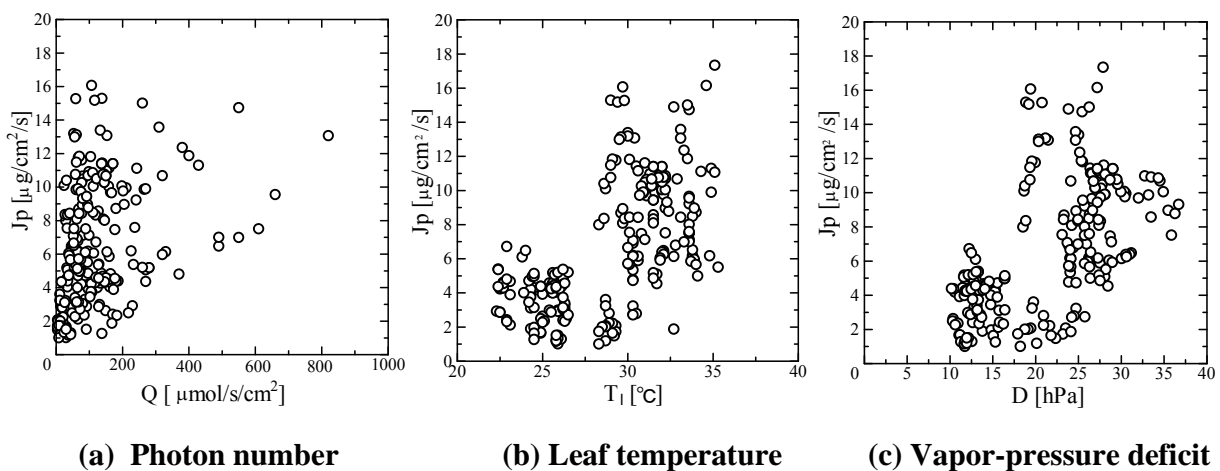
Energy Balance of Isolated Single Tree

It is difficult to measure the amount of transpiration and the radiation balance of tree body planted in urban area directly. Then, a forecast model from the surrounding metrological elements is examined based on the fragmentary measured results. A camphor tree is selected as for the major target.

Measurement of Transpiration Rate of Single Leaf

The transpiration rate for each unit area of each leaf J_{pobs} [$\mu\text{g}/\text{cm}^2/\text{s}$] was obtained by using the diffusion-type polometer on the site. Air temperature T_a , leaf temperature T_l , relative humidity R_h , and photon number Q in specific wavelength region (400-700nm) of solar irradiation effective for photosynthesis were measured at the same time as the surrounding metrological element. The object tree is a camphor tree with the height of about 10m in the campus of Osaka Prefecture University. This kind of tree is widely planted on urban parks or streets.

The relation among transpiration rate J_p of single leaf of camphor tree, photon number Q , leaf temperature T_l , and vapor-pressure deficit D is shown in Figs.2 (a)-(c) for the measured data in 2008. The vapor-pressure deficit D is defined by the difference between the saturated water vapor pressure on the leaf side and the water vapor pressure of the atmosphere. Some correlation is admitted between the transpiration rate and these weather conditions, respectively. However, there is comparatively large dispersion, and it is understood that the transpiration action is affected by the combined influence of various factors. Moreover, the measured transpiration rate was only obtained for single leaf. Therefore, it is necessary to guess the amount of transpiration from the whole tree to evaluate the energy budget of single tree as described later.



(a) Photon number (b) Leaf temperature (c) Vapor-pressure deficit
Figure 2. Relation among transpiration rate of single leaf of camphor tree, photon number, leaf temperature, and vapor-pressure deficit

Prediction of Transpiration Rate of Single Leaf

Physiological factors of the plant besides the factors to control evaporation relate to the transpiration rate. For instance, the transpiration rate approaches constantly for incident number of photons, that is, for solar irradiation as shown in Fig.3 for the measured data in 2005 to 2008.

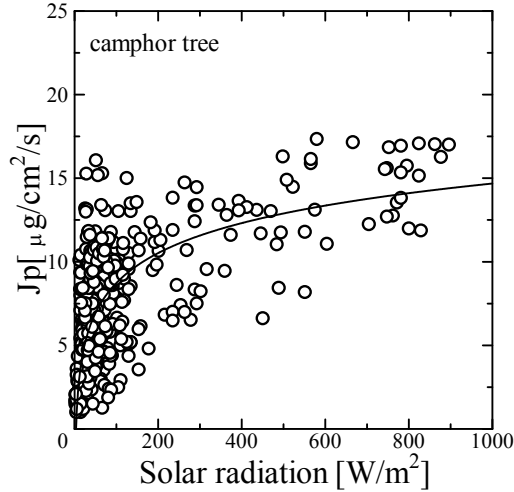


Figure 3. Relation between transpiration rate and solar irradiation

The transpiration rate of single leaf is generally expressed by the following equation.

$$J_p = \frac{g_b g_s (\rho_l - \rho_c)}{g_b + g_s} \quad (1)$$

where g_b is the conductance of boundary layer on leaf side, g_s is the stomatal conductance, ρ_l is the water vapor concentration on leaf side and ρ_c is the water vapor concentration of surrounding atmosphere, respectively.

The physics model that Jarvis proposed as a model of the stomatal conductance was employed in the present study. For Jarvis's model (Jarvis 1976), the stomatal conductance is shown by Eq.(2) as a product of independent function of photon number Q , vapor-pressure deficit D , and leaf temperature T_l . Those values are regularized so that each function may also take the value of 0-1.

$$g_s = g_{smax} f_1(Q) f_2(D) f_3(T_l) \quad (2)$$

The values of g_{smax} and the parameters in each function are decided to suit the measured data most according to the nonlinear least square method. The transpiration rate J_{ppre} is predicted by obtaining g_s by using these values, and substituting the obtained value for Eq.(1). Figure 4 shows the correlation of the actual measured data J_{pobs} and the predicted values. As for the transpiration rate from single leaf, the prediction is said to be almost possible according to the surrounding weather conditions.

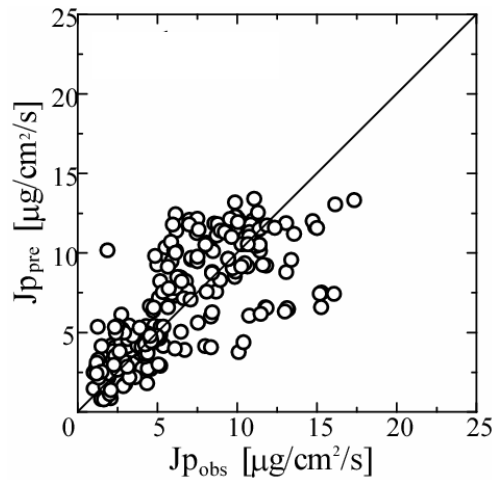


Figure 4. Correlation between measured data and predicted values of transpiration rate of single leaf of camphor tree

Model of Radiation Transfer and Transpiration of Single Tree

In general, because it was known that the camphor tree grows thick in spheroidal, the tree canopy was assumed to be a globe. The influence of the branch and the trunk is disregarded. All leaves are assumed to be attached in parallel to ground, and not to interfere mutually. A double layer of the spherical shell was adopted as a group of leaves. The leaf area index was given 8.0. This index is defined as the ratio of gross area of all leaves that exist in the upper side with area of ground surface. In the globe shown in Fig.5, the axis of polar coordinates ($\theta = 0^\circ$) is assumed to be a perpendicular direction, and the surface area is divided into the direction of the zenithal angle θ and azimuthal angle ϕ at intervals of 5° , respectively. The radiation balance is estimated for each element.

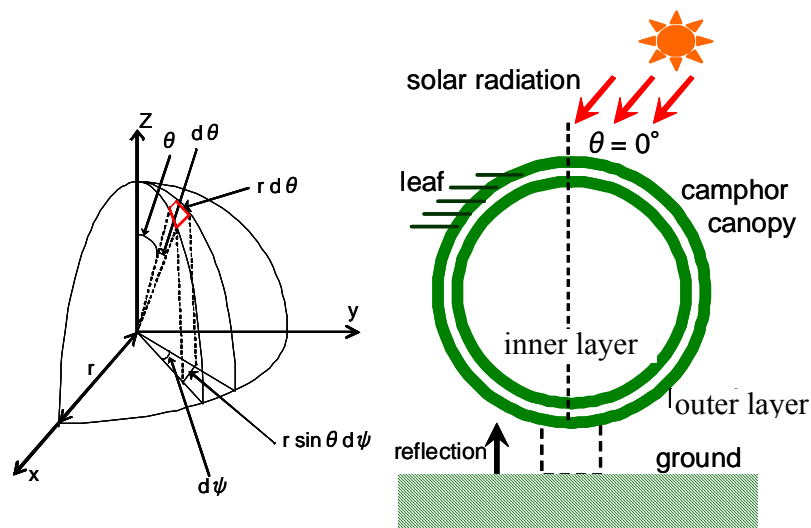


Figure 5. Outline of tree model of camphor tree

The solar radiation transfer is handled separately for two wavelength bands PAR (Photosynthetically Active Radiation) and NIR (Near Infrared Radiation). PAR is about 0.4 to 0.7 μm effective for photosynthesis. NIR is a longer wavelength band than PAR. The reflectivity (0.1 and 0.4) and the transmissivity (0.1 and 0.5) of plant leaf are greatly different in PAR and NIR. Direct solar radiation accounts for 90 % of global solar radiation under a fine day, and the ratio is different in two wavelength bands. It is assumed that direct solar radiation is equally received in the hemisphere in the incident direction. The diffuse solar radiation from the sky and the ground is assumed to be received in the upper and lower hemisphere, respectively. The characteristic of ground is assumed to be the same as the reflection property of leaves in consideration of the meadow where the camphor tree of the measuring object was planted.

As for the infrared radiation, the sky radiation and the emitted radiation from leaves are considered in the upper hemisphere, and the emitted radiation from ground and leaves are considered in the lower hemisphere. 0.98 is given to the emissivity of leaf and ground. The emissivity has been reported to be more than 0.8 excluding the metals (Yoshida, et al. 2004). The surface temperature of ground is equal to the leaf temperature. The leaf temperature T_l [$^{\circ}\text{C}$] was requested by using the following empirical equation (Ikezawa, et al. 1995) expressed by air temperature T_a [$^{\circ}\text{C}$] and horizontal total solar radiation S_r [W/m^2].

$$T_l = 0.882T_a + 0.0036S_r + 1.86 \quad (3)$$

Transpiration rates J_{ppre} for unit area and unit time are requested by inputting the metrological elements such as air temperature, relative humidity, and solar radiation to Jarvis's model [Jarvis 1976]. Next, the amounts of transpiration for unit time from each leaf element are requested by multiplying the element area by J_{ppre} . The whole amount of transpiration from the object tree was calculated by adding them. The validity of the tree model is verified by the comparison with the amount of transpiration obtained from the measured results of the sap flow speed as described later.

Estimated Energy Budget of Isolated Single Tree

The energy budget was estimated by using the meteorological data on July 15 in 2008 until 9:00AM to 3:00PM at intervals of ten minutes. The amount of transpiration from a camphor tree was calculated by the method of the foregoing paragraph. Latent heat flux IE was obtained by multiplying the evaporative latent heat by the estimated value, and dividing in the projected area of the tree seen from the sky. Net radiation flux Rn was also obtained by the method of the foregoing paragraph. Because the temperature difference on both sides of the leaf was small, the conductive heat flux and thermal storage were disregarded. Sensible heat flux H was assumed to be the remainder. Figure 6 (a) shows the time variation of the energy budget of a camphor single tree. $IE(\text{model})$ in this figure means the estimated latent heat flux. $IE(\text{measurement})$ means the latent heat flux obtained from the measured result of the sap flow speed as explained by the post-paragraph. Figure 6 (b) shows each element of the radiation balance. The absorbed amount of each wavelength band of PAR and NIR is clarified for solar radiation. The absorbed amount in the inner layer in double spherical shell layers shown in Fig. 5 was separately displayed. Infrared radiation from the atmosphere and the leaves were displayed.

As shown in Fig. 6 (a), the estimated latent heat transfer became about 35-50 percent of the net radiation. It was clarified that the sensible heat transfer also took the key role for the

thermal transfer of the isolated single tree. The difference is admitted in the energy budget of the isolated tree compared with the colony tree like the forest. It has been understood that the ratio to the net radiation of the latent heat transfer is almost similar to the herbs plant described later. As shown in Fig. 6 (b), it has been understood that the majority of the absorbed solar radiation to the leaves is occupied in the wavelength band of PAR that influences the transpiration activity. It was shown that the absorbed one in the outer layer in double spherical shells as shown in Fig. 5 was completely predominant. The time variation of the infrared radiation is not large, and the state of the radiation cooling continues. As a result of measuring the difference between the leaf temperature and the air temperature, the difference of both was small with about 1 °C.

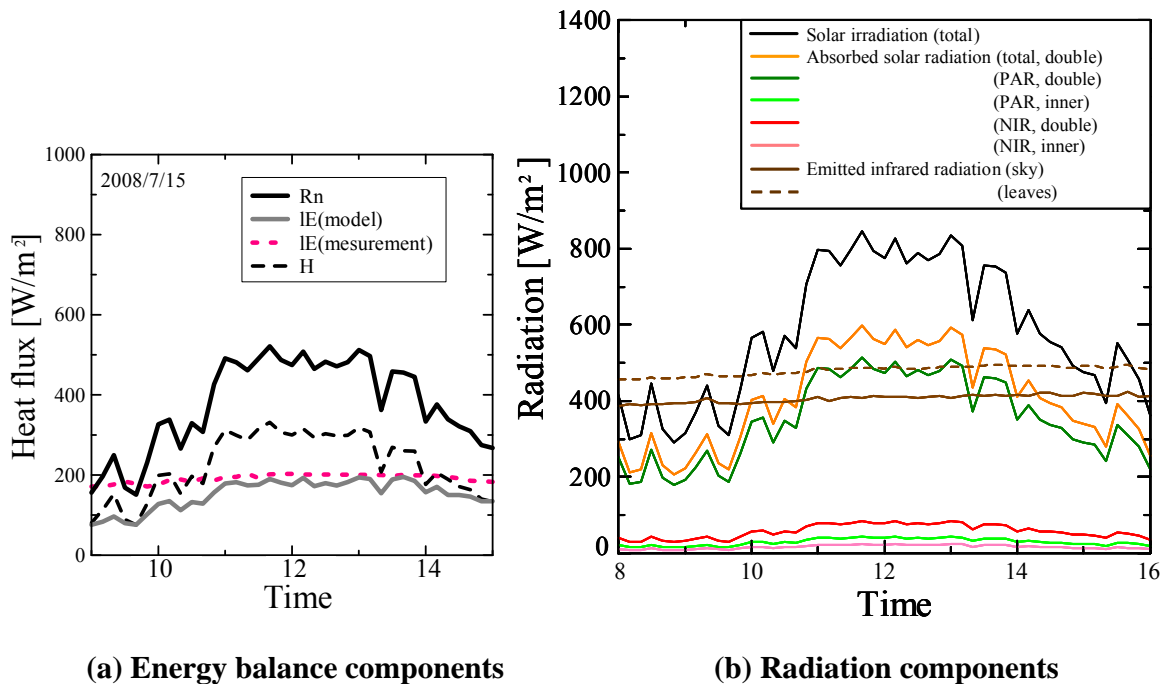


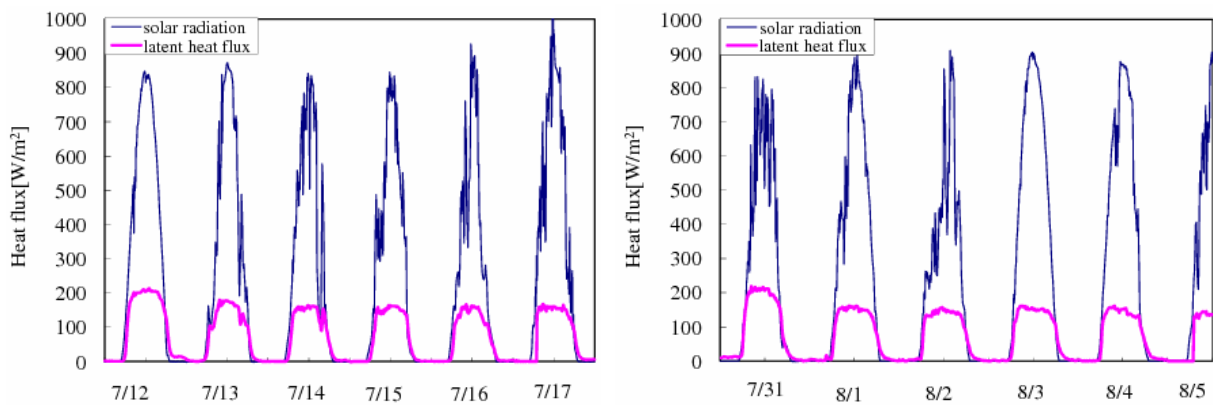
Figure 6. Estimated energy budget of isolated camphor tree in daytime of summer

Measurement of Sap Flow Speed in Trunk of Tree

The sap flow speed that flowed in the trunk of camphor tree by using the Granier's method (Granier 1987) was measured to verify the accuracy of the amount of transpiration estimated by the tree model. TDP-80 of the Dynamax Co. was used for the measurement. Two pair sensor of T type thermocouple are arranged in the device, and they are inserted in the trunk of tree. The heater is built into the upper sensor, and heat is given regularly. The measured data is temperatures difference between these two sensors. When the sap flow speed vanishes, the temperature difference between sensors becomes the maximum. If the relation between temperature difference and the sap flow speed is known, the calculation of the sap flow speed easily becomes possible. The amount of transpiration of a single tree can be obtained by grasping the cross sectional distribution of the sap flow speed, and integrating in the cross section. The measurements were done in two points of the southern and northern parts at 70mm and 15mm from the surface every minute. The core sample was extracted to request the sectional area in the sap wood part that the sap passed, and the area was visually decided. The latent heat transfer was

obtained by multiplying the sap flow speed by the area. The ginkgo tree was measured as well as the camphor tree.

Figures 7 (a) and (b) show the relation between the latent heat transfer and the global solar irradiation of camphor tree and ginkgo tree obtained from the sap flow speed, respectively. It has been understood that either tree also consumes 20-30 percent of global solar irradiation as latent heat transfer. Figure 6 shows the latent heat transfer IE (measurement) on July 15 obtained according to the sap flow speed. It roughly agreed to the latent heat transfer obtained according to the model, and the validity of the tree model could be confirmed.



(a) Camphor tree

(b) Ginkgo tree

Figure 7. Relation between global solar irradiation and latent heat transfer

Energy Balance of Potted Plant

The energy budget of a potted plant is examined in outdoor. The radiation balance measured directly without a model. Hibiscus that was a plant for general gardening was used as an examination target. The measurement was performed in the open space in the campus of Osaka Prefecture University. The diameter of the potted hibiscus used is about 55cm, the height on the soil side in the pot is about 45cm, and the leaf area index is 1.71. Water was given enough to the pot on the morning of the measurement day, the pot where the soil face had been covered with the vinyl film was weighed with an electronic balance every 30 minutes, and the amount of transpiration of the plant was obtained. The measurement items and the equipments are shown in Table1. All data except for the transpiration were recorded with data logger (EKO, SOLAC V) every minute. The measurement height of air temperature, humidity, and wind velocity is 1.0m.

Table 1 Measurement items and instruments

Items	Instruments
Air temperature/Relative humidity	Thermohygrometer
Leaf and ground temperature	Thermocouple
Radiation flux	Net radiometer
Wind velocity	Super sonic anemometer
Transpiration	Top-loading balance

The net radiation in the potted plant is obtained as follows.

$$Rn = S \downarrow + L \downarrow - Sp \uparrow - Lp \uparrow \quad (4)$$

$$Rn = H + IE + G \quad (5)$$

where Rn is net radiation, $S \downarrow$ is incident solar radiation, $L \downarrow$ is incident infrared radiation, $Sp \uparrow$ is reflected solar radiation from the plant, $Lp \uparrow$ is emitted infrared radiation from the plant, H is sensible heat flux, IE is latent heat flux and G is conductive heat flux [W/m^2]. The upward radiation on the plant canopy is obtained in consideration of the influence that the sensors catch excluding the potted plant. The radiation balance on the bottom of canopy consists of the transmitted solar radiation through the plant canopy, the reflected solar radiation from the ground, the emitted infrared radiation from bottom of plant canopy and the ground. The conduction heat transfer in the plant canopy was thought to be 0 from the fact that the surface temperatures difference between the inside and outside of leaf was not admitted.

The measured results on the energy budget of a pot-grown plant are summarized. The evaluated time is 30 minutes. Figure 8 shows the ratio of the latent heat transfer flux obtained by using the projected area of the plant to the net radiation flux. The net radiation flux has increased so that the absorbed radiation flux received under the plant canopy may increase in the pot-grown plant compared with the colony plant. However, the transpiration rate has the tendency to reach the ceiling for the solar radiation irradiated on account of the physiological trait of the plant as shown in Fig.3. Therefore, the ratio of the latent heat transfer flux to the net radiation flux was only about 50 percent at most even in summer when the transpiration is active, and decreased in autumn. The measured date when the temperature in daytime is more than $25^\circ C$ is expediently expressed as summer. It has been reported that the latent heat transfer accounted for about 70 percent of the radiation transfer in the forest (Kanda, et al. 1997). The ratio of the latent heat transfer in the pot-grown plant was obviously smaller than that in the forest. It agrees with

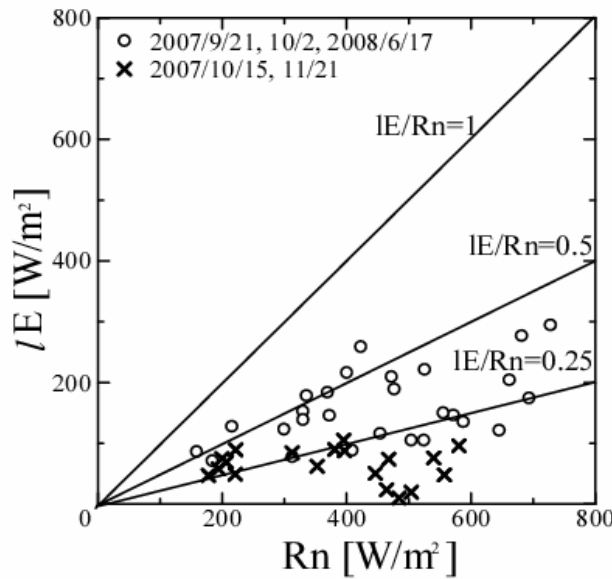


Figure 8. Relation between net solar radiation and latent heat transfer of potted plant

the above-mentioned result of isolated single camphor tree, too. The measured results of pot-grown plant also have the possibility that the transpiration control according to the soil moisture content decrease of the pot is influenced. It can be guessed that the plant keeps the energy balance by enlarging the difference between leaf temperature and air temperature as much as possible, and increasing the sensible heat transfer when the stress by soil moisture or air temperature joins. It was observed that there was a maximum difference between the leaf temperature and the air temperature of 7 °C according to the weather condition. It is a problem examined in the future. From the above-mentioned results, it is necessary to pay attention to not only the transpiration action of plant but also the sensible heat transfer from plant.

Heat Transfer Coefficient on Leaf Side

The heat transfer coefficient on the leaf side was examined in consideration of the active sensible heat transfer from plant. First of all, the heat transfer coefficient on the leaf side of pot-grown plant was presumed on the basis of the sensible heat transfer of the crowd of leaves estimated from the measured data of energy balance. The measurements were executed by using the potted hibiscus and a mock body of color and shape modeled on hibiscus made by dry material, that is artificial plant, on November 21 in 2007 and June 17 in 2008. The artificial plant doesn't have the transpiring action. Therefore, it is thought that the sensible heat transfer is more exactly appreciable from the living plant. The exchange of sensible heat of the artificial plant and the potted hibiscus was assumed to be performed on the leaf front and the back. Thus, the heat transfer coefficient of leaf side of the artificial plant and the potted hibiscus was calculated from the difference between the sensible heat transfer flux, the leaf area index, and the temperature difference between the leaf surface and the surrounding air as shown by the following equation.

$$\alpha = \frac{H}{(T_l - T_a) \times 2 \times LAI} \quad (6)$$

where α is heat transfer coefficient [W/m²/K], H is sensible heat flux [W/m²], T_l is leaf temperature [°C], T_a is air temperature [°C] and LAI is leaf area index.

The heat transfer coefficient of paper was measured in outdoor for the comparison with the potted plant. The measurement was executed from summer to autumn in 2008 for black paper. The measurement place was the above-mentioned open space, and the measuring instruments and the measurement items are the same as Table 1. Paper of some kinds of sizes was used to examine the effect of the size on the heat transfer coefficient. Figure 9 shows the averaged heat transfer coefficient for 30 minutes of the leaves of potted hibiscus and artificial plant, and the different sizes of paper. The temperature difference between air and leaf of hibiscus was about 1-5°C. The average leaf sizes of the potted hibiscus and the artificial plant were about 5 to 7 cm, respectively. The observed range of the wind speed narrowed comparatively because the wind was weak on the measured dates of the heat transfer coefficients of the paper. It has been understood that the heat transfer coefficients of potted hibiscus and artificial plant tend to be larger than those obtained from Jurges' formula expressed by Eq.(7) generally used in the field of architectural engineering or those obtained from the empirical equation used in heat transfer field of mechanical engineering.

chapter, and then the heat transfer coefficient α was calculated by using Eq.(6). Figure 10 shows the results of camphor tree. The heat transfer coefficients of leaf side of the camphor tree were from about 20 to 30 W/m²/K against the surrounding wind speed from 0.5 to 1.5m/s, and were the same level as those of the potted plant. The heat transfer coefficients of plant leaf and small size piece of paper are larger than those values obtained from the empirical equations. As the physical explanation, it is enumerated that the thermal boundary layer on the object side does not develop enough and the turbulent mixing with the main current is active. As a result, the difference between the air temperature and the leaf temperature tends to become small. It will be necessary to discuss the correlation between the heat transfer coefficient of the leaf and the canopy structure in the future.

Evaporation Efficiency of Isolated Tree and Potted Plant

The mass transfer coefficient κ was obtained from Eq.(8) by assuming the analogy with the heat transfer coefficient α . The evaporation efficiency β was calculated by using Eq.(9) from the ratio of the evaporation rate of the camphor tree estimated according to the model or the measured value of the potted hibiscus E and the product of mass transfer coefficient κ and the vapor-pressure deficit ($X_s - X_a$). The evaporation efficiency is defined as a ratio of an actual transpiration rate to the evaporation rate on water surface.

$$\kappa = \frac{\alpha}{C_p \times L_e} \quad (8)$$

$$\beta = \frac{E}{\kappa \times (X_s - X_a)} \quad (9)$$

where κ is mass transfer coefficient [kg/m²/s], C_p is specific heat of air [J/kg/K], L_e is Lewis number (= 0.83), β is evaporation efficiency, E is actual evaporation rate [kg/m²/s], X_s is saturated absolute humidity at surface temperature [kg/kgDA] and X_a is absolute humidity of air [kg/kgDA], respectively.

Figure 11 shows the evaporation efficiency of isolated camphor tree and potted hibiscus. The evaporation efficiency was about 0.05-0.2 in daytime regardless of solar irradiation. The evaporation efficiency of natural lawn of watering enough and water retentive pavement in daytime after water sprinkling is reported to be 0.7 and 0.2-0.3, respectively (Umeda, et al. 2006 and Misaka, et al. 2007). The evaporation from soil in addition to the transpiration from leaves was assumed to be active in natural lawn. These are used on the roof or the road as one of the mitigation countermeasures to decrease air temperature in urban area. On the other hand, the evaporation from the soil under each plant is not included in the present study. The tree is thought to contribute largely to mitigate thermal environment in urban space, considering depending only on rainwater and creating shade in summer, though the evaporation efficiency of isolated tree is not large.

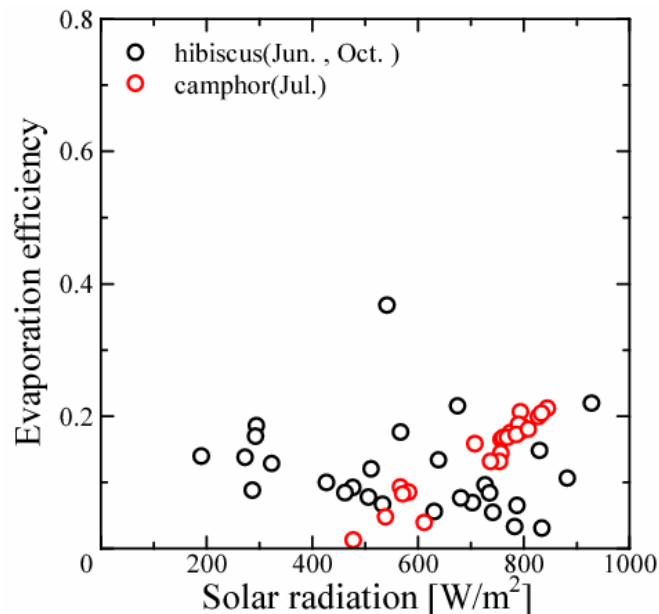


Figure 11. Evaporation efficiency of isolated tree and potted plant

Summary

1. The latent heat transfer of isolated tree and potted plant occupied 50 percent at most to the radiation transfer, and then the sensible heat transfer took an important role in viewpoint of the energy balance of plant.
2. It was found out that the heat transfer coefficient on the leaf side was larger than that on the semi-infinite flat plate. One of the main causes was guessed to be small size of leaf on the basis of the theory of boundary layer.
3. The evaporation efficiency of tree was smaller than that of natural lawn including the evaporation from the soil, but did not changed greatly regardless of the solar irradiation.

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