Shinichi Kinoshita

Numerical Evaluation of Heat Budget in Tree Crown Considering the Detailed Structure

Shinichi Kinoshita[1], Atsumasa Yoshida[2], Shoko Hashida[3]

[1] *Osaka Prefecture Univ., 1-1 Gakuen-cho, Naka-ku, Sakai 599-8531, Japan, kinosita@me.osakafu-u.ac.jp*

[2] *Osaka Prefecture Univ., 1-1 Gakuen-cho, Naka-ku, Sakai 599-8531, Japan, ayoshida@me.osakafu-u.ac.jp*

[3] *Meisei Univ., 2-1-1 Hodokubo, Hino, Tokyo 191-8506, Japan, shokoh@es.meisei-u.ac.jp*

1. Introduction

Planting trees is one of the countermeasures to urban heat island because of the cooling effect by the transpiration or the sunlight cover effect. It is difficult to construct the large scale forest in urban area, so isolated trees such as roadside tree are generally planted. In the case, it is desirable that trees are efficiently located on understanding the performance of heat exchange between the tree crown and the atmosphere. The heat budget related to the performance of a tree cannot be directly measured in detail. In this study, heat budget of isolated plant unit is numerically evaluated with thermal plant model including radiation transfer model for net radiation and transpiration model for latent heat transfer, and the numerical results are validated by comparison with that of outdoor measurement for a potted plant.

1. Heat budget in tree crown and decision of Ross's radiative transfer equation parameter

Heat budget is evaluated as the balance of net radiation, sensible and latent heat transfer between the leaves and the atmosphere and conduction heat transfer to the foliage. Conduction heat transfer is omitted in this study, because thermal thickness of leaves is thin. Latent heat transfer related to transpiration on leaf surface can be evaluated by Jarvis model[1)]. Net radiation of foliage is evaluated by solving the Ross's radiation transfer equations[2)] as following.

$$r_j \frac{\partial i_d(x,r)}{\partial x_i} = -a(x)G(x,r)i_d(x,r) \tag{1}$$

$$r_j \frac{\partial I(x,r)}{\partial x_j} = -a(x)G(x,r)I(x,r) + a(x)\int_{\omega'=4\pi} \Gamma(x,r,r')I(x,r')d\omega' + a(x)e(x,r) \tag{2}$$

$$r_j \frac{\partial i_{ir}(x,r)}{\partial x_j} = -a(x)G(x,r)i_{ir}(x,r) + \frac{1-\varepsilon}{\pi}a(x)\int_{\omega'=4\pi} \Gamma_R(x,r,r')i_{ir}(x,r')d\omega' + \frac{\varepsilon}{\pi}a(x)G(x,r)\sigma(T_L+273.15)^4 \tag{3}$$

$$e(x,r) = \int_{\omega'=4\pi} \Gamma(x,r,r')i_d(x,r')d\omega' \tag{4}$$

$$G(x,r) = \frac{1}{2\pi}\int_{\omega'=2\pi} g(x,r_L)\left|(r,r_L)\right|d\omega' \tag{5}$$

$$\Gamma(x,r,r') = \frac{T}{\pi}\Gamma_T(x,r,r') + \frac{R}{\pi}\Gamma_R(x,r,r') \tag{6}$$

$$\Gamma_T(x,r,r') = \frac{1}{2\pi}\int_{\omega_L=2\pi} g(x,r_L)H\left[(r,r_L)(r',r_L)\right]d\omega_L \quad \Gamma_R(x,r,r') = \frac{1}{2\pi}\int_{\omega_L=2\pi} g(x,r_L)H\left[-(r,r_L)(r',r_L)\right]d\omega_L \tag{7}$$

$$H[f] = f \quad if \quad f \geq 0 \qquad H[f] = -f \quad if \quad f < 0 \tag{8}$$

where a: leaf area density, G: extinction coefficient of foliage, i_d and I: intensities of direct and diffuse insolation, respectively, i_{ir}: long wavelength radiation, g: configuration function, Γ: scattering function of foliage, x: position vector, r: direction vector of radiation, r_L: normal vector of leaf surface, T and R: transmittance and reflectance of a single leaf, ε: emittance of single leaf, T_L: leaf temperature, ω: solid angle. Sensible heat transfer is by difference between the net radiation and latent heat transfer.

In the prediction of net radiation of foliage, computer graphics (CG) model with software AMAP, which can draw tree characteristics such as shapes of a tree crown and a leaf and leafing arrangement on a branch, is applied to decision of structure parameters of leaf area density a and configuration function of leaf surface direction vectors g which are included in Ross's radiation transfer equations in plant vegetation. It is necessary for evaluation of the net radiation to consider direct and diffuse insolation from the sky and scattering light in tree crown for the component of short wavelength and thermal radiations from surroundings including atmospheric radiation and from leaf surfaces for the component of long wavelength. This time the effect of direct solar radiation expressed in eqs.(1) and (3) is only considered for evaluating net radiation absorbed in tree crown. Leaf temperature which is necessary for evaluating the thermal radiation from leaf surfaces and transpiration rate is evaluated as satisfying the heat budget on leaf surface. However, this time the leaf temperature is predicted the following relation which is obtained from the results of infrared photograph of tree crown and atmospheric temperature and solar radiation simultaneously measured in open space.

$$T_L = 0.882T_a + 0.0036S + 1.86 \tag{9}$$

where T_a: atmospheric temperature [deg.C], S: solar radiation toward tree crown [W/m^2]. Parameters of Jarvis model in transpiration of leaves is decided by measurement of transpiration rate of actual leaves of several kinds of trees. By applying the numerical simulation, shielding efficiency of insolation and ratio of latent and sensible heat transfers to net radiation of isolated and vegetated tree are evaluated for several kinds of trees.

Computation domain is located as the whole body of an isolated plant is covered, and the domain is divided into some cuboid control volumes. The amount of absorbed solar radiation in a control volume involving leaf foliage is evaluated by subtracting the amount of extinction by scattering from total amount of extinction in the volume. Solar radiation is evaluated with divided into PAR (photosynthetic availability radiation) and NIR (near infrared radiation), and the reflectance and transmittance in each wave region is set to 0.1 and 0.1 for PAR and 0.4 and 0.5 for NIR, respectively.

2. Outdoor measurement of heat budget of hibiscus

Outdoor measurements of heat budget for potting flesh and artificial flowers of hibiscus as samples are performed at open space of A5 bldg. of Osaka Prefecture University from 10:30 to 16:00 in every 30 minutes on August 2nd 2012. Enough water is poured into the potting, and soil of potting is cover with plastic film after leak of water from the bottom of potting is stopped in order to control moisture evaporation. The weight of potting is measured every 30 minutes, and the amount of transpiration is measured from the difference of the weight. Global solar radiation, atmospheric radiation, air temperature and relative humidity are measured every 10 second, and wind velocity is measured in 10Hz and is translated in the averaging time of 30minutes. Leaf temperatures both of flesh and artificial plant are measured with thermo-couples by selecting one sheet of leaf in each direction. Thermo-couple is installed on the back of leaf. Net radiation to leaf foliage is evaluated in considering radiations from the sky, ground and the soil surface of potting as a thin circle flat plate. Leaf area index (LAI) of flesh hibiscus is measured by the following procedure. Areas of three leaves selected at random are measured, and the total leaf area is estimated by multiplying the average area of selected three leaves and the number of leaf of a whole hibiscus. LAI is calculated as the ratio of the total area of leaves to the projection area from the top of potting, and

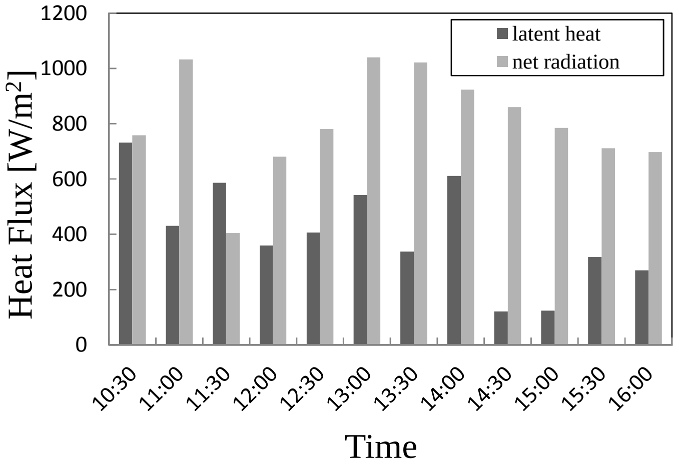

Fig.1 Heat budget of Hibiscous by outdoor measurement.

Table 1 Numerical conditions

August 2nd 2012	10:00	12:00	14:00
Zenith angle (degree)	32.4	16.9	30.8
Azimuth angle (degree)	-66.6	3.49	64.2
Global solar radiation (W/m^2)	777	559	820
Atmospheric temperature (deg.C)	35.5	33	35.4
Relative humidity (%)	38.1	50.2	41.7
Wind speed (m/s)	1.9	1.7	1.8

the value of this time is evaluated to be 7.3.

Resulted heat budgets are shown in Fig.1. This figure shows that latent heat transfer becomes decreases from 14:00. It is considered that the phenomenon is caused by decreasing water remaining in the potting in the latter half of measurement because of not pouring the additional water. Decrease of net radiation from 11:00 to 13:00 is caused by change in cloudy weather.

Parameters of Jarvis model of stomatal conductance model are identified from the results in the above experiment. This time the stomatal conductance is evaluated without the factor about leaf temperature because of insufficient number of transpiration rate data. Figure 2 shows a CAD model of hibiscus, and figure 3 shows the numerical result of heat budget by using the obtained model parameters. By comparing between figs.1 and 3, both net radiation and latent heat transfer in numerical analysis is smaller than those in experiment. LAI of CAD model in numerical analysis is 4.6, and flesh hibiscus used in experiment is leafier than CAD model. It is considered that the difference of LAI leads to the underestimation in numerical analysis.

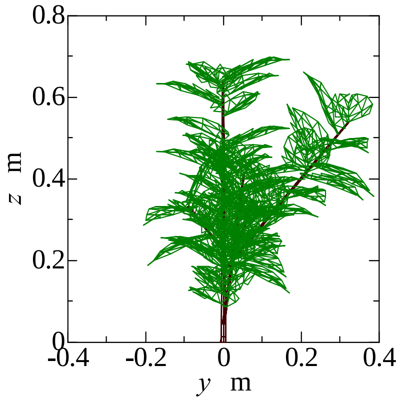

Fig. 2 CAD model of hibiscus

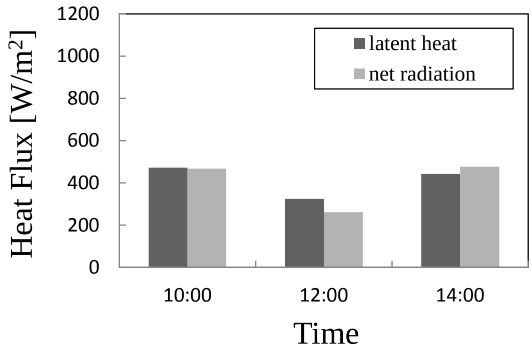

Fig. 3 Numerical evaluation of heat budget of hibiscus

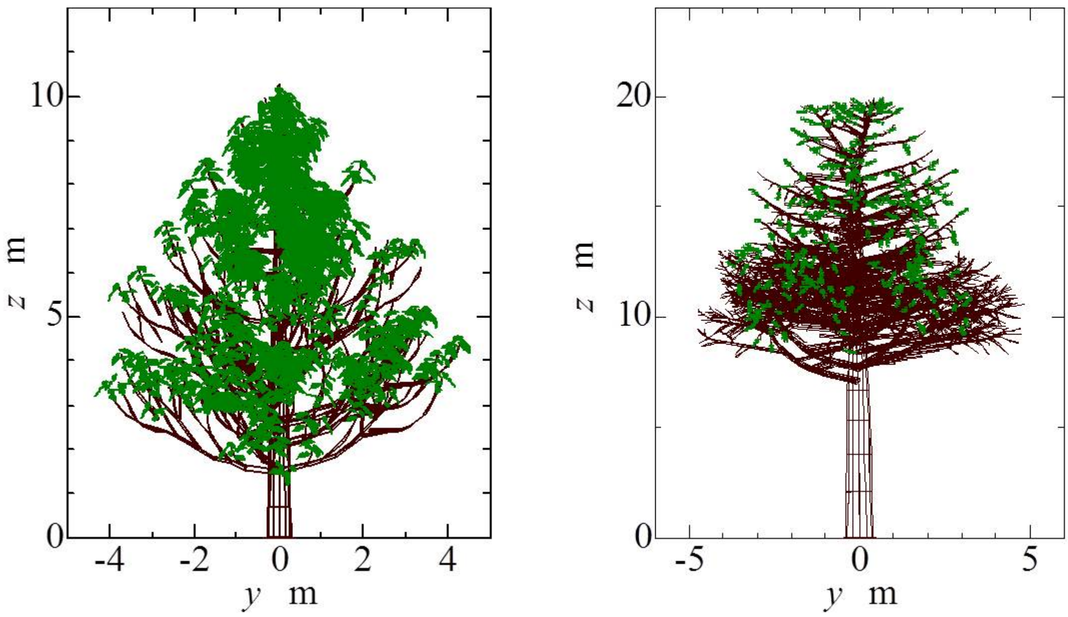

Fig. 4 CAD models of camphor and ginkgo

Table 2 Numerical results of heat budget for three kinds of plants

	Hibiscus			Camphor			Ginkgo		
Height of tree (m)	0.698			10.2			19.7		
Projection area (m^2)	0.12			125			170		
LAI	4.6			3.3			4.6		
Aug. 2nd 2012	10:00	12:00	14:00	10:00	12:00	14:00	10:00	12:00	14:00
Transmission ratio of insolation (%)	43	37	41	38	37	37	57	57	58
Shielding ratio of insolation (%)	57	63	59	62	63	63	43	43	42
Net radiation (W/m^2)	468	262	477	414	260	429	417	253	399
Latent heat flux (W/m^2)	473	326	443	394	331	382	305	277	297

3. Numerical analysis of heat budget in an isolated tree crown

Numerical analyses based on CAD models of two kinds of isolated tree, camphor and ginkgo, are performed. Numerical conditions of sun position, solar radiation, air temperature and humidity, wind speed are same as that in the analysis of hibiscus. Parameters of Jarvis model of camphor and ginkgo is obtained from another investigation of transpiration rates of these trees.

Table 1 shows the numerical results for three kinds of tree. For all of them, net radiation and latent heat flux are almost same value. In this numerical analysis, it assumes that a part of incident radiation energy on a tree is absorbed on leaf surface and the scattering light from leaf surface is emitted outside of the computation domain without contribution to absorption in tree crown. It is considered that the ratio of scattering is a half of incident solar energy and the assumption not to contribute to absorption in other area in tree crown is overestimate. Therefore, it is important for accurate analysis of heat budget in tree crown to evaluate the effect of the scattering between leaves.

Acknowledgment

This work was supported by JSPS KAKENHI Grant Number 25420612.

References

1) Jarvis, P.G., 1976: The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field, *Phil. Trance. R. Soc. Lond*. **B. 273**, 593-610.
2) Ross, J. and Nilson, T., 1975: Radiation Exchange in Plant Canopies, *Heat and Mass Transfer in the Biosphere Part 1 Transfer Processes in the Plant Environment*, 327-336.