Annual Journal of Hydraulic Engineering,
JSCE VOL. 41 (1997)

A New Device for Continuous Recording of The Heat Balance at The Soil Surface in Greenhouses

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Abstract

A new device for continuous computing and recording of the energy balance terms at the bare soil surface in greenhouses is described with some of its principle advantages and characteristics. Bare soil condition in greenhouses was simulated in this study to understand well the effect of the greenhouses on the distribution of the heat balance terms at the ground surface. The downward net radiation flux was directly measured; sensible heat, latent heat and soil heat fluxes were calculated from the data of the air temperature, air relative humidity, the surface temperature and the air velocity. The results of a field trial over a bare soil surface demonstrate the new device's reliability and operational effectiveness for experimental periods of many days.

Keywords : greenhouses, bare soil, net radiation, sensible heat, latent heat, soil heat flux .

1. Introduction

Determination of the diurnal variation of the net radiation, sensible heat, latent heat and soil heat fluxes requires the availability of some form of the energy distribution at the earth-atmosphere interface. This question can be treated quantitatively by considering the equation for the energy budget for a layer of surface material. Depending on the nature of the surface, this layer may consist of water, or of some other substrate like soil, canopy or snow; although this layer can be taken to be infinitesimally thin, it may sometimes even comprise a lake or a vegetational canopy over its entire depth. For practical purposes, the energy budget equation in a general form is

$$R_n - L_e E - H + L_p F_p - G + A_h = \frac{\partial W}{\partial t} \qquad \text{..........(1)}$$

where the energy fluxes toward the layer are taken as positive and those away from it as negative. R_n is the net radiation flux density at the upper surface of the layer, L_e is the latent heat of vaporization, E is the evaporation rate from the upper surface of the layer, H is the sensible heat flux into the atmosphere, L_p is the thermal conversion factor for fixation of carbon dioxide, F_p is the specific flux of carbon dioxide, G is the soil heat flux leaving the layer at its lower boundary, A_h is the energy advection in the layer expressed as specific flux, and

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$\frac{\partial W}{\partial t}$ is the rate time of the energy storage per unit area in the layer; in the case of an ice or snow layer this last term may include the energy consumed by fusion, and L_e may have to be replaced by L_s, the latent heat of sublimation.

The exact nature of several of the terms depends on the type of the layer or substrate for which the energy balance is written. Actually, for many practical purposes, several of them can be omitted. For a simple lumped system, when effects of unsteadiness, ice melt, photosynthesis and lateral advection can be neglected (Brutsaert, 1982), the energy budget is,

$$R_n - L_e E - H - G = 0 \qquad \text{..........(2)}$$

where all terms have been previously defined. The order of magnitude and diurnal variation of all terms in Eq. (2) have been investigated in the case of a grass covered surface (Pruitt et al., 1968; Brutsaert, 1982), in the case of mature and maize canopy (Perrier et al., 1976), at the surface of a deep water body (Yasuda, 1975), and at the surface of a shallow lake of a mean depth 2 m (Raupach, 1978). However, these methods require a very detailed models in order to describe the continuity of the heat fluxes at the interface properly and they can not be used in the case of greenhouses. On the other hand, recently greenhouses have been widely used for cultivating some kinds of fruits, vegetables and some other plants, to provide a special climatic conditions different from those of the available weather outside the greenhouses. Many shapes and patterns of greenhouses can be constructed depending on the type of the intended plant for cultivation, the requested climatic conditions and the economical costs. The authors of this paper present a fundamental study on a practical technique, which enables precisely to evaluate continuously the rate of the heat fluxes at the earth-atmosphere interface under some conditions similar to those in some patterns of greenhouses.

2. Measuring Apparatus

The measuring apparatus mainly consists of three parts as follows

(1) A net radiometer for measuring the net radiation.

(2) Three thermometers for measuring the temperature of the soil just beneath the surface (at a depth of about 0.001 m).

(3) A new equipment for measuring evaporation has been proposed by Watanabe and Tsutsui (1994). Figure 1 shows a schematic view of this new equipment. The main idea of this equipment depends on the fact that, if some parts of the ground surface are covered by a box made of transparent sheets and the air is injected from one side and extracted from the opposite side the absolute humidity of the extracted air increases when, the vapor is coming out from the ground surface by evaporation or by evapotranspiration. The dimensions of the box are 0.45 m height, 0.50 m width and 0.60 m length. The air is continuously injected into the box from one

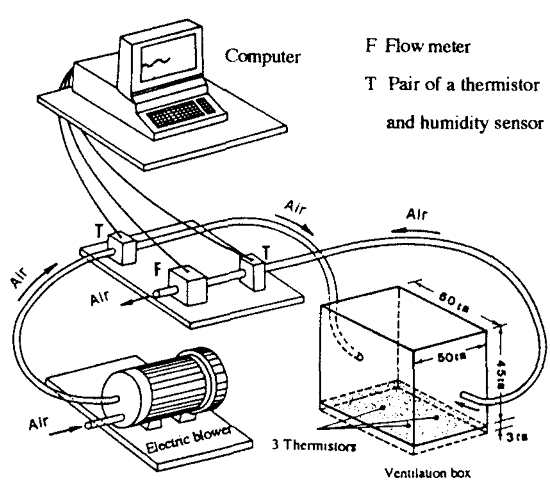

Fig. 1. Schematic view of the evaporation measuring technique.

side and extracted from the other side by using an electric blower. During the experiment the relative humidity and temperature of both injected and extracted air are measured by a couple of humidity and thermistor sensors. Kurokuwa et al. (1995) and Abdel-Lah et al. (1996) have checked the accuracy of this equipment for measuring evaporation and evapotranspiration. The climatic conditions in the ventilation box of this equipment (as shown in Fig. 1) are closely to those in the simple pattern of greenhouses shown in Fig. 2.

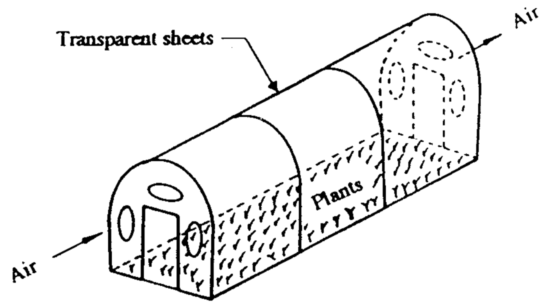

Fig. 2. Definition sketch of a simple pattern of greenhouses.

3. Field Experiment

An experimental plot of 0.6 x 0.5 m was selected inside the campus of Saitama University, Japan. The soil was described as a sandy clay soil. To understand better the diurnal behavior of the main terms in the surface energy balance under wetter conditions, such as would occur after periods of irrigation, the plot was saturated. Three thermistors as shown in Fig. 1 were installed just beneath the ground surface (at a depth of about 0.001 m) and distributed over the area to measure the soil temperature at the very thin top layer of the soil during the experiment. The arithmetic mean of the three measured values was considered as the soil surface temperature. The experiment was begun after the wetting process by a few days to allow the settlement of an equal soil moisture distribution. The field experiment was made in the period from 16th to 18th of October 1996. Fifteen minute average values of the air flow rate, net radiation, relative humidity of the injected and extracted air, temperature of the inflow and outflow air and the soil temperature just beneath the surface were measured .

4. Description and Analysis

4.1. Observed data

Some of the observed data were plotted as shown in Figs. 3 through 6. The air flow rate was almost constant during the experiment with an average value of $8.119 \times 10^{-3}\ m^3/s$. The diurnal changes of the measured net radiation is presented in Fig. 3 and it appears that the three days of the field experiment have

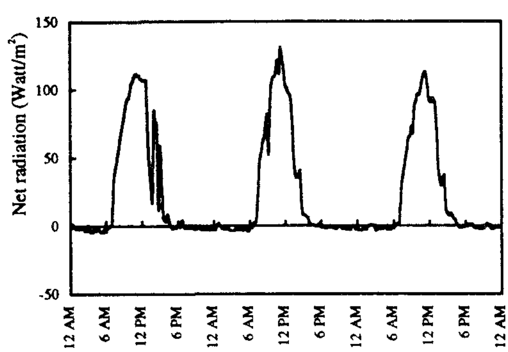

Fig. 3. Diurnal changes of the measured net radiation.

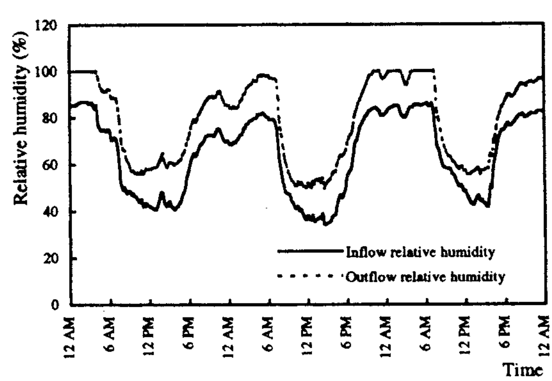

Fig. 4. Measured relative humidity of the inflow and outflow air.

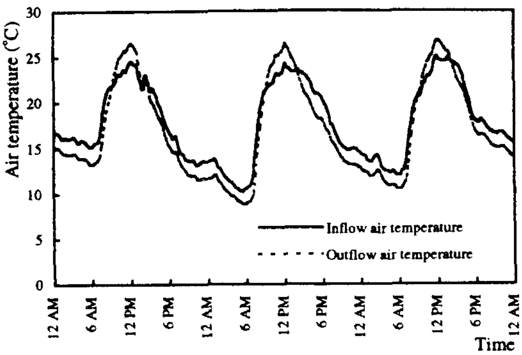

Fig. 5. Measured temperature of the inflow and outflow air.

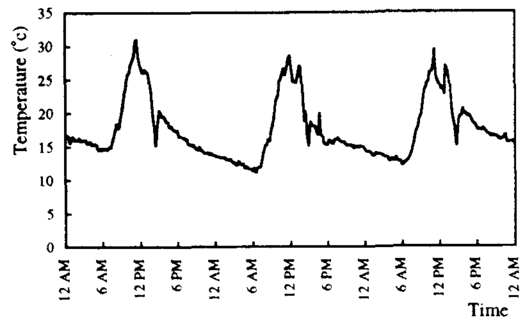

Fig. 6. Diurnal variation of the soil temperature just beneath the surface (at a depth of 0.001 m).

almost the same degree of clearness. To check the effect of the net radiation on the air relative humidity, air temperature and the soil temperature at the very thin top layer, their observations were plotted as shown in Figs. 4 through 6 respectively. It is observed that, each of them has a trend follows that of the net radiation.

4.2. Net radiation flux

A common characteristics of most energy budget methods is that, they require the determination of the net radiation. The net radiation at the ground surface was measured directly with a net radiometer positioned at 0.30 m above the ground surface and located outside the box. The radiation components were measured in the short-wave and long-wave ranges. Two solarimeters, one for exposure from above and one for exposure from below, were used for measurements. Net radiation from the upper and lower hemispheres was recorded using a radiation balance meter. To check the effect of the transparent sheets of the box on the passing net radiation, the net radiation was measured inside and outside the box at the same time. The two values were compared and it was found that, the influence is too small to take into consideration. The diurnal variation of the measured net radiation flux during the experiment is shown in Fig. 3.

4.3. Latent heat flux

The absolute humidity of the injected and extracted air from the box must be calculated first to estimate the evaporation rate from the soil surface in the box. The absolute humidity of the air can be calculated from its temperature and relative humidity (Brutsaert, 1982) as follows

$$e_a = \frac{e_a^* h}{100} \qquad \text{..........(3)}; \qquad \beta = \frac{0.622 e_a}{R_d T_a} \qquad \text{..........(4)}$$

where e_a is the water vapor pressure in the air, e_a^* is the saturation water vapor pressure at the air temperature, h is the relative humidity, β is the absolute humidity, R_d is the gas constant for dry air, T_a is the air temperature, and the constant 0.622 is the ratio of the molecular weights of water and dry air. From the air flow rate and the calculated absolute humidity of the injected and extracted air the evaporation rate can be simply calculated from the following basic equation as

$$E = \frac{-Q(\beta_{out} - \beta_{in})}{A} \qquad \text{..........(5)}$$

where E is the evaporation rate, β_{out} and β_{in} are the absolute humidity of the extracted and injected air respectively, Q is the volumetric flow rate of the air and A is the covered area by the box. The diurnal variation of the calculated evaporation rate during the field experiment is displayed in Fig. 7. This figure illustrates the general behavior of the evaporation rate from bare soil surface in greenhouses after irrigation when the available water stored in the soil profile is being depleted. Because the experiment took place during a drying period, the daily cyclic behavior is superimposed on a trend of decreasing daily mean evaporation. The mass of the evaporated water per meter square per day was 4.886, 3.849 and 2.930 kgs for the three days of the experiment successively. A similar trend in daily mean evaporation after rainfall is also found by (Van Bavel et al., 1965; Black et al., 1969), although their measurements were made in the actual weather conditions.

Finally, the latent heat flux can be calculated from the multiplication of the evaporation rate by the latent heat of vaporization. The latent heat of vaporization (L_e) depends mainly on the temperature of the evaporating surface (Brutsaert, 1982) and can be obtained from

$$L_e = \frac{R_d T_s^2}{0.622 e_s^*} \frac{de_s^*}{dT_s} \qquad \text{..........(6)}$$

where T_s is the soil surface temperature as the evaporating surface, e_s^* is the saturation water vapor pressure at the soil surface temperature, $\frac{de_s^*}{dT_s}$ is the rate of change of the saturation vapor pressure with respect to the soil surface temperature and all other variables have been previously defined.

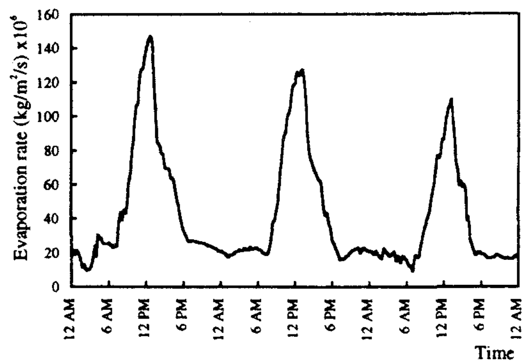

Fig. 7. Transient changes of the evaporation rate during the field experiment.

4.4. Sensible heat flux

If we assume that, the sensible heat from the soil is taken by the moving air inside the box, and all other heat sources or sinks can be neglected, the continuity equation is given as

$$H = \frac{-Q\rho C_d \left(T_{a(in)} - T_{a(out)}\right)}{A} \qquad \text{...........(7)}$$

where H is the sensible heat flux, Q is the volumetric flow rate of the air, ρ is the air density, C_d is the specific heat of dry air, $T_{a(in)}$ and $T_{a(out)}$ are the temperature of the injected and extracted air respectively and A is the bare soil area in the box. The sensible heat flux into the atmosphere was calculated using Eq. (7).

4.5. Soil heat flux

The soil heat flux evaluates the amount of the energy flux leaving or entering the surface layer of the soil at its lower boundary. The direction of this energy term depends on the fact that, when different parts of a body are at different temperatures, heat flows from the hotter parts to the cooler. In general, the energy budget method allows the determination of one of the terms of the general Eq. (1), or any simple form of it, when all the remaining terms can be determined by some independent methods. Therefore, the soil heat flux was estimated from Eq. (2) as the remaining unknown term, while all other terms except it have been previously measured or calculated.

4.6. Diurnal variation of the main terms in the energy budget

In Fig. 8 the average fifteen-minute values of the net radiation, latent heat, sensible heat and soil heat fluxes measured or calculated by the methods described in the previous paragraphs are presented. As shown in this figure, all of these terms depend mainly on the net radiation. The reason is that, the net radiation strongly affects the air relative humidity, the air temperature and the soil temperature at the very thin top layer as mentioned before. Compared with the results obtained by other authors under natural weather conditions, the latent heat flux term in the greenhouses constructions is quite larger and accordingly the soil heat flux. This nature implies that, the relatively high air velocity inside the greenhouse tends to increase the latent heat flux and accordingly decreases the soil temperature at the very thin top layer. On the other hand, and when the downward net radiation is small, the heat is supplied from the underlaying and the surrounding soil layers in the form of a soil heat flux to compensate this energy lack. The result of this energy balance system shows that, the soil heat flux also becomes larger than that under the natural weather conditions especially during the evaporation peaks.

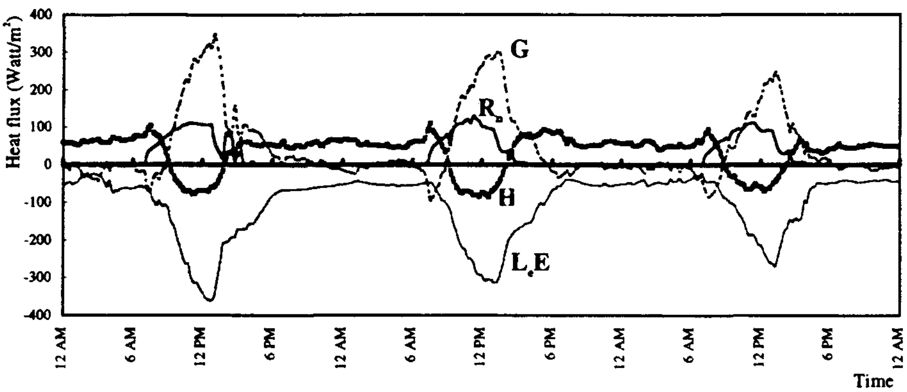

Fig. 8. Measured and calculated components of the surface energy balance: measured net radiation R_n, calculated evaporation flux L_eE, calculated sensible heat flux H and calculated soil heat flux G.

Conclusions

With this portable and simple equipment a satisfactory estimation of all energy balance terms in the field can be continuously made. The obtained results are;

(1) A new practical technique for estimating the heat balance terms in greenhouses was proposed,

(2) The energy budget in greenhouses can be easily and continuously evaluated by this technique,

(3) The wind in general increases the evaporation and accordingly the latent heat flux increases,

(4) When the latent heat flux is increased while the downward net radiation is small the soil heat flux tends to overcome this energy deficit and becomes larger than that under natural weather conditions, and

(5) The general feature of the energy budget in the greenhouses is well described.

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