ESTIMATION OF TRANSPIRATION FROM A TREE BY USING TWO-SENSOR TYPE EVAPORATION METER

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A new technique for the in-situ measurement of the transpiration from a tree was proposed in this paper. This technique is composed of the following two points: (a) application of two-sensor type evaporation meter to the transpiration measurement from leaves of tree (b) estimation of total transpiration from a tree. Transpiration from some kind of trees such as mango, rubber and mulberry could be successfully measured. Total transpiration from a mango tree was also well estimated by the technique. It was concluded that the technique can be widely used not only in Japan but also in South East Asian countries.

Key Words: *two-sensor type evaporation meter, transpiration, accuracy check, transpiration distribution, South East Asia*

1. INTRODUCTION

The environmental problem related to the water shortage is very severe during last decade all over the world. The proper estimation of water demand is indispensable for water resources management. Transpiration is a very important factor in determining the amount of necessary water.

Although many methodologies have been proposed by many researchers (Brustsaert[1)], Boast[2)]) and many types of equipment could be available, most of them are complex and difficult to apply. The average evapotranspiration from wide area can be roughly estimated by using some meteorological data (Penman[3)], Monteith[4)]). However, the transpiration from a tree is strongly influenced not only by the meteorological conditions but also by many other factors, such as tree type, age of trees and leaves, soil type, saturation of soil and so on. These effects cannot be well evaluated by the meteorological methods. From the reason, development of the direct measurement of evapotranspiration is strongly needed. However, direct measurement techniques such as lysimeter technique cannot apply to the arbitrary point in the field. In this paper, we have proposed application of two-sensor type evaporation meter developed by Watanabe K. (1989), which has been successfully used in many applications (Watanabe [5), 6), 7)], Aye Aye Thant et. al[8)], Kyi Myint Thwin et. al[9)]). The main advantage of this equipment is simplicity both in theory and practical application.

The technique by using this two-sensor type evaporation meter described is mainly proposed for South East Asia countries to estimate the transpiration because the technique is relatively inexpensive, easy to travel and transport. Moreover the transpiration rate can be measured accurately with minimal disturbance to the surrounding environment. In this study, transpiration rate from mulberry plant and rubber tree in Japan under humid condition and that from mango tree in Thailand under tropical condition were measured. Basic idea of this new technique is described in this paper with some results of field measurement.

2. TRANSPIRATION MEASUREMENT FROM A TREE

(1) Transpiration measurement from a leaf surface

The basic idea of the measurement is schematically illustrated in **Fig. 1**. When a leaf is not moving with wind and the width of leaf is large enough, thin laminar flow layer is formed over the leaf surface. In the layer, the vapor flux coming from the leaf surface by the transpiration is essentially transported in the vertical direction by the molecular diffusion to the leaf by the absolute humidity gradient.

The absolute humidity linearly increases towards the leaf surface in this layer. Watanabe et. al (1991) have checked the relationship between the thickness of laminar flow layer with different wind velocity. They have also checked the accuracy of the equipment for measuring evaporation both in the laboratory and field, for measuring the evaporation rate from the rock surface in the tunnel.

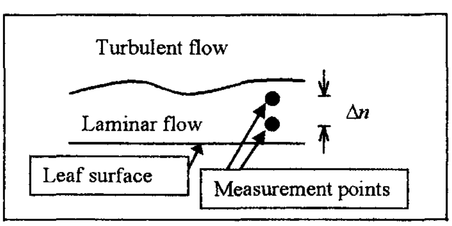

Fig. 1 Idea of the transpiration measurement

The absolute humidity can be approximated from the temperature and relative humidity. The absolute humidity can be estimated by the following equation (Brustsaert 1982).

$$e_a^* = 101325\, exp(13.3185 t_{Ra} - 1.9760 t_{Ra}^2 - 0.6445 t_{Ra}^3 - 0.1229 t_{Ra}^4) \quad (1)$$

$$t_{Ra} = 1 - \frac{373.15}{T_a} \quad (2)$$

$$e_a = \frac{e_a^* H_r}{100} \quad (3)$$

$$\theta = \frac{0.622(10^{-3}) e_a}{R T_a} \quad (4)$$

Where, e_a^* = saturated vapor pressure at air temperature (Pa), T_a = air temperature (K), e_a = vapor pressure (Pa), H_r = relative air humidity (%), θ = absolute humidity (mg/m^3), R = gas constant for dry air (287.04 JKg^{-1}K^{-1}), and the constant 0.622 is the ratio of the molecular weights of water and dry air. The absolute humidity gradient can be calculated as,

$$\frac{\partial \theta}{\partial n} = \frac{\theta_2 - \theta_1}{\Delta n} \quad (5)$$

θ_1 and θ_2 are the values of absolute humidity for lower and upper sensor (mg/m^3) and the Δn is the distance between lower and upper sensor (m). Transpiration rate can be calculated by the following equation.

$$Tra = -D_m \frac{\theta_2 - \theta_1}{\Delta n} \quad (6)$$

Tra is the transpiration rate (mg/m^2/s) and D_m is the molecular diffusion coefficient (m/s). The molecular diffusion coefficient D_m was estimated by the use of the following equation [10].

$$D_m \approx 2.41\times10^{-5} + 1.5\times10^{-7}(T-15) \quad (7)$$

T is the temperature (° C). *Tra* can be estimated by 2 absolute humidity values measured at 2 points of different heights.

(2) Experimental apparatus

The measuring apparatus mainly consists of two pairs of humidity sensor and thermistor. The shape of the sensor part of the equipment used (Tokyo Keisoku ETH 2101) is shown in **Fig. 2**.

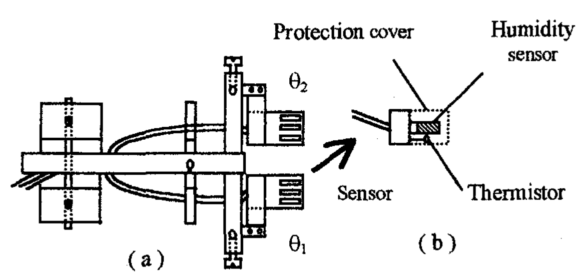

Fig. 2 Schematic diagram of evaporation sensor

As shown in **Fig. 2b**, the humidity sensor is plated shape and its size is about 5mmx5mm. The thermistor is of spherical shape with 2mm diameter. A protection cover shields humidity sensor and thermistor. The size of the protection cover is 6mm thick, 1.5cm wide and 2cm long. The humidity and the temperature at the center height of the protection cover (3mm from the bottom of the cover) can be measured. The distance Δn between two pairs of the humidity sensor and the thermistor was fixed as 5mm.

Data measured by each sensor are sent to the microcomputer to calculate the absolute humidity and the transpiration rate from the plant. All data obtained are stored in the data logger. The response time of the sensor is about 20 seconds and finally 5 minutes average values were stored in the data logger.

Based on the Watanabe's experimental results the thickness of laminar layer is larger than 1cm when wind velocity is smaller than 0.06 m/s[6]. The thickness of 1cm is enough to measure precisely the absolute humidity.

(3) **Transpiration from a tree**

The two-sensor type evaporation meter can measure transpiration from leaf surface. However, a tree has many leaves. A technique how to estimate the total transpiration from a tree is needed. The technique and procedure have shown in **Fig. 3**.

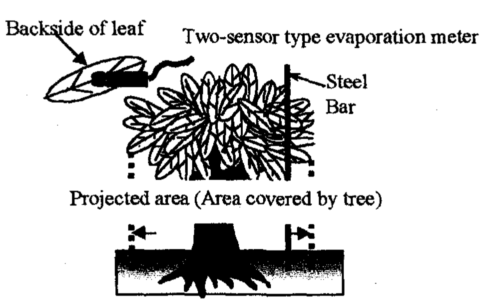

Fig. 3 Schematic presentation of transpiration measurement

Two-sensor type evaporation meter measured the transpiration rate from the both sides of the leaf and the average transpiration values for back and front T_{totb} and T_{totf} are estimated. The following procedure is used in estimating the total area of leaves. First, a steel bar is vertically standing at many locations under tree and the number of leaves intercepting the bar is measured. Then the average number of leaves covering unit projected area of the tree N is calculated. When the projected area of tree A is estimated, total numbers of leaves can be expressed as N×A. The total transpiration rate from a tree T_{tot} can be simply calculated by the following equation.

$$T_{tot} = (T_{totf} + T_{totb}) \times N \times A \qquad (8)$$

3. CHECKING THE ACCURACY OF TWO-SENSOR TYPE EVAPORATION METER

Before applying the equipment for the actual measurement of the transpiration, accuracy of the measurement by two-sensor type evaporation meter was checked both in the laboratory and field.

(1) Accuracy check in the laboratory and field

Accuracy check of the sensor has already reported by Watanabe et. al.[6]. Accuracy check similar to the previous study was performed. Accuracy in the laboratory by comparing measured evaporation rate with weight losses recorded by a balance. A cup filled with wet soil was prepared. The weight of the specimen decreases if the water from the specimen evaporates. The weight increases when the specimen sucks the vapor in air. At the same time evaporation meter also measured the vapor flux just above the upper surface of the specimen. Accuracy check was carried out in the laboratory and field for a period of 6 hours under a little wind velocity condition. The comparisons between 2 evaporation measurements were shown in **Fig. 4 and 5.** It was found that the evaporation rate measured by the equipment showed the good agreement with the evaporation rate calculated by the balance.

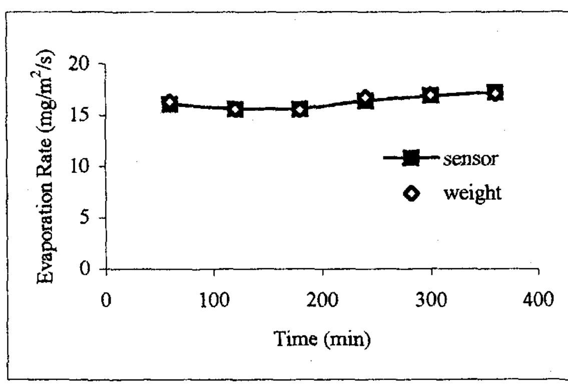

Fig.4 Accuracy check for sensor with wet soil in laboratory

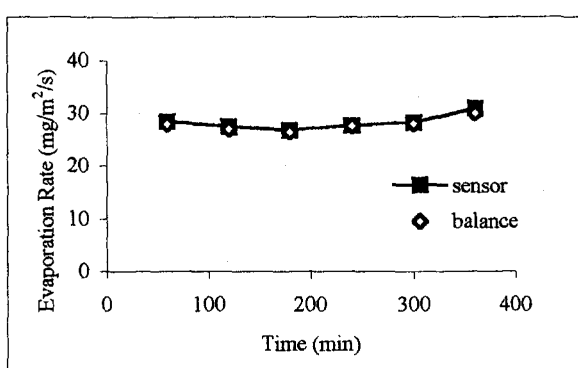

Fig.5 Accuracy check for sensor with wet soil in field

(2) Numerical simulation of absolute humidity distribution and transpiration rate

The numerical simulation in estimating the distribution of absolute humidity and transpiration rate due to effect of leaf size and wind velocity is performed by solving the following governing flow equation for two-dimensional convection-dispersion equation subjected to boundary condition described later.

$$\frac{\partial\theta}{\partial t} = D_m \frac{\partial^2\theta}{\partial x^2} + D_m \frac{\partial^2\theta}{\partial y^2} - V\frac{\partial\theta}{\partial x} + Tra \qquad (9)$$

Where θ = absolute humidity (gm/m^3), t = time (sec), D_m = diffusion coefficient (m/s), x = distance in x direction (m), y = distance in y direction (m), V= velocity in x direction (m/s), Tra = transpiration rate (mg/m^2/s). Eqn. (9) can be solved numerically if the boundary conditions are defined. Domain of the numerical analysis is as shown in **Fig. 6**.

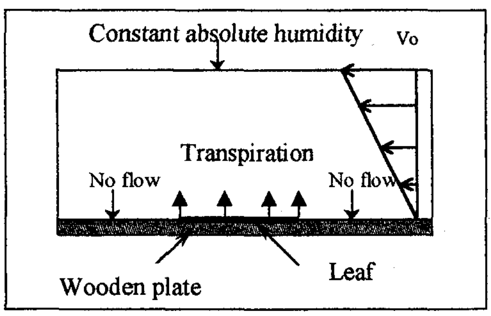

Fig. 6 Boundary condition of the domain

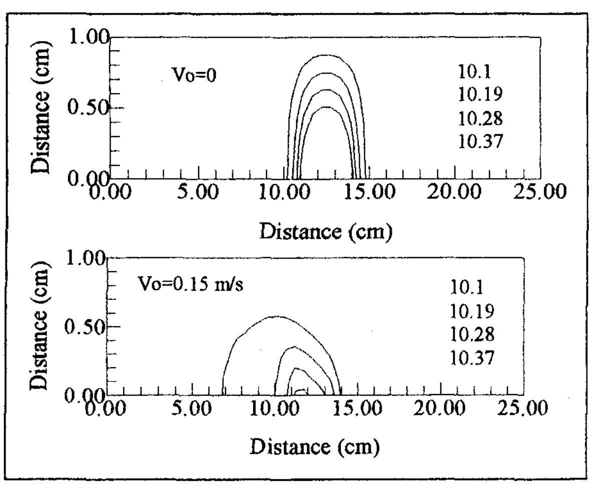

Fig. 7 Absolute humidity distribution for 3 cm leaf width with different wind velocity

Boundary conditions applicable to the transpiration experiments carried out in this study are as follow. Velocity profile is assumed to be changed linearly in linear layer as shown in **Fig. 6**. V_o is the velocity at the upper boundary of laminar layer. For bottom boundary condition, it is considered as no flow except for the leaf area. Left, right and top of the boundary layers are considered as constant absolute humidity because these boundaries are the border of the laminar and turbulent flow layer. As mention before, thickness of laminar layer is assumed as 1cm *in this study*. Although the formulated model is approximated, the effect of velocity may be evaluated. **Fig. 7** and **8** are the simulated results of the absolute humidity distributions for 3cm and 5cm-leaf width with different wind. From the results of these figures, we can calculate the transpiration rate and then we can compare the measured and calculated transpiration rate for 3cm and 5cm-leaf width with different wind velocity as shown in **Fig. 9** and **10**. When the V_o increases, calculated value is a little distributed in the down stream area of leaf. In this study, we assumed V_o=0.15 m/s as the maximum wind velocity. From those results, it is calculated that the transpiration measurement has much error when the wind velocity becomes high. Measurement must be performed under low wind velocity condition. When wind velocity becomes V_o=0.15 m/s, the measured value is less than around 60% of the true values. It is concluded that measurement should be performed under small wind velocity condition.

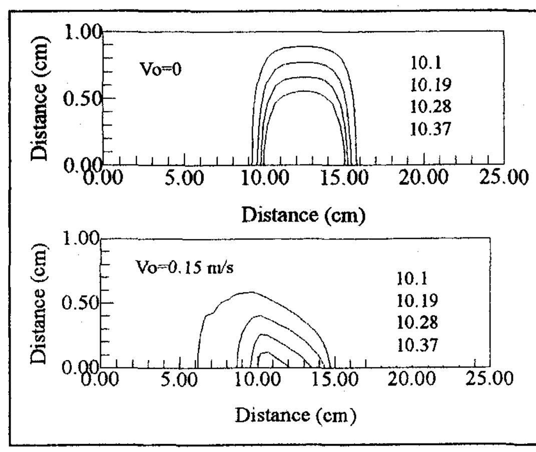

Fig. 8 Absolute humidity distribution for 5 cm leaf width with different wind velocity

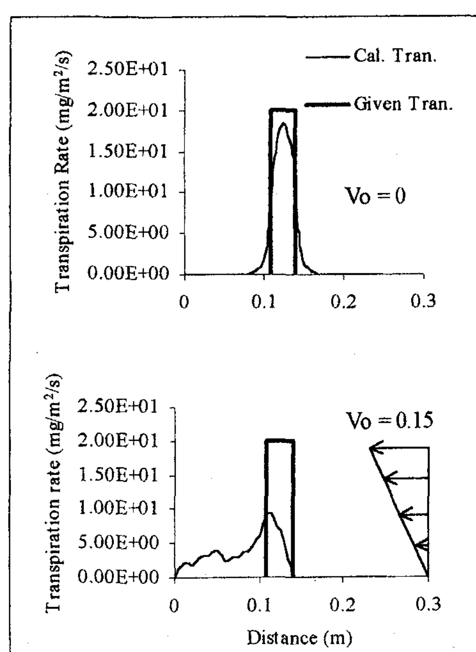

Fig.9 Comparison of measured and given transpiration rate for 3cm leaf width

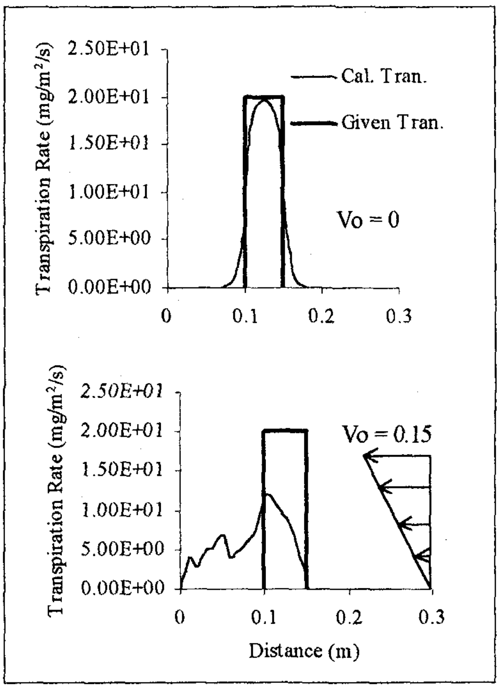

Fig. 10 Comparison of calculated and given transpiration rate for 5cm leaf width

4. TRANSPIRATION MEASUREMENT

(1) Transpiration distribution

Transpiration measurement was carried out in the campus of Saitama University. Mulberry and rubber trees were selected for the measurement. Prior to the measurement, it was observed that transpiration was occurred from the both side of the leaf. All measurement was carried out covering a tree branch by transparent sheet for wind protection condition. **Fig. 11** illustrates the results of transpiration rate from the both side of mulberry plant leaf and rubber tree leaf. Results of transpiration rates from back side of old and young leaf from mulberry plant is shown in **Fig. 12**. Transpiration rates for different leaves of mulberry plant under sunshine and shadow condition during sunny day are illustrated in **Fig.13**. Transpiration rate for different leaves of rubber tree under laboratory condition is shown in **Fig. 14**. The transpiration distributions from mulberry plant under sunshine condition and rubber tree under laboratory condition are illustrated in **Fig. 15** and **16**.

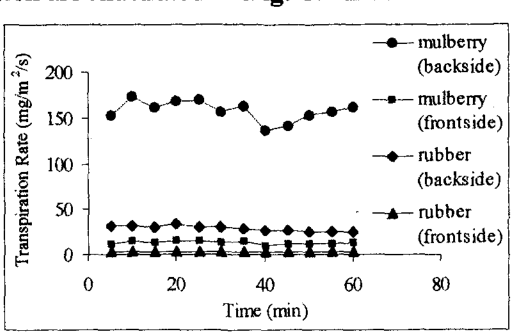

Fig. 11 Transpiration rate from both side of mulberry and rubber tree

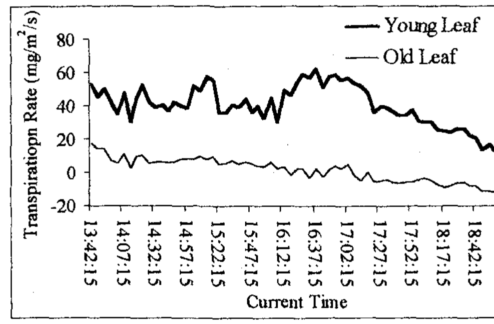

Fig. 12 Transpiration rate from backside of old and young leaf of mulberry plant

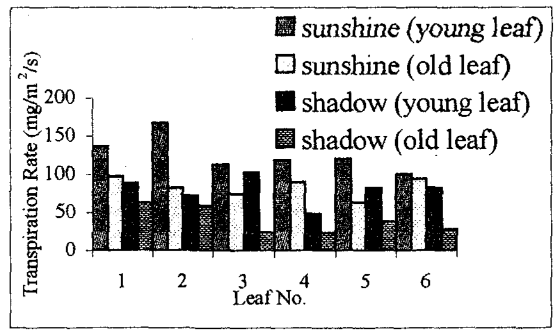

Fig. 13 Transpiration rates for different leaves of mulberry plant under sunshine and shadow condition

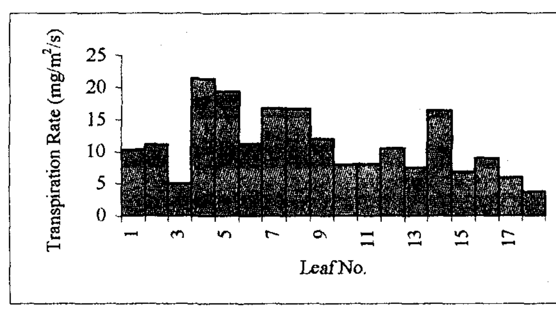

Fig. 14 Transpiration rate for different leaves of rubber tree under laboratory condition

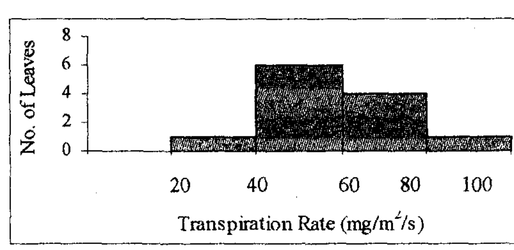

Fig.15 Transpiration distribution in mulberry plant under sunshine condition
(in Japan, average values of back and front sides)

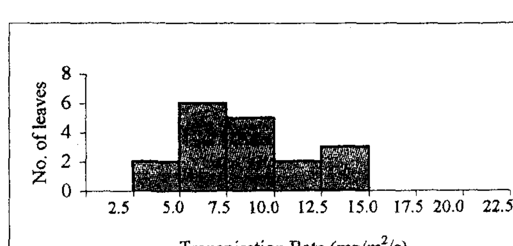

Fig. 16 Transpiration distribution in rubber tree under laboratory condition
(in Japan, average values of back and front sides)

(2) Total transpiration from a mango tree

A transpiration measurement was carried out in the campus of the Thammasat University, Thailand. A mango tree of which is about 5m high was selected for the measurement. Prior to the measurement, it was observed that transpiration occurred only on the backside of the leaf of mango. **Fig. 17** illustrated the projected area of the tree. The total area A was about 8.6m^2. The number of leaves intercepting a vertical steel bar was measured at different 19 points. The average number of leaves N was 5.9. 24 leaves were selected for the measurement. Wind was carefully protected with covering branch of tree by a transparent plastic sheet. Transpiration distribution from mango tree in Thailand is illustrated in **Fig.18**. The distribution is scattered because the transpiration from leaves was much influenced by the age of leaf and the radiation condition. The average transpiration was about 70 mg/m^2/s under sunshine condition. On the other hand, the average transpiration in shadow area was about 20 mg/m^2/s. The average transpiration rate was roughly calculated as 48.12 mg/m^2/s. With inputting those values into equation (8), the total transpiration from this mango tree can be estimated as 2.44 g/s (8.78 l/hour) or 1.00 mm/hour. These values are thought to be reasonable under the natural condition. It was found that the measurement procedure is simple and highly practical. For more precise estimation, other parameter such as the ratio between the shadow leaves to all leaves should be estimated.

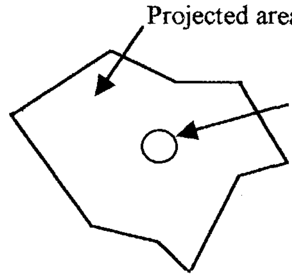

Fig.17 Schematic diagram of projected area of a mango tree

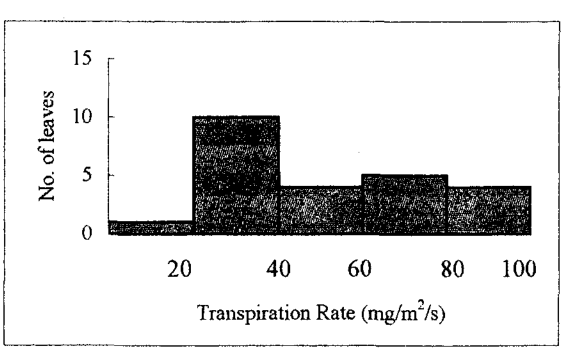

Fig.18 Transpiration distribution in mango tree under sunshine condition
(in Thailand, average values of back and front sides)

5. CONCLUSIONS

We successfully devised a simple transpiration measurement, which is relatively inexpensive, easy to operate and transport for the developing countries like South East Asian countries. It can give the satisfactory estimates of transpiration rate. Both laboratory and field tests show the high accuracy of the two-sensor type evaporation measuring technique. Prior to the measurement, observation of transpiration from the leaf surface must be necessary. Leaf sizes greater than 3cm give the highly accurate results and the effect of wind on the measurement must also be evaluated. Before estimating the total transpiration rate from a tree, radiation condition, type of plant and the age of leaf must be studied more in detail. Even the leaf transpirates from the both sides, the backside of the leaf transpirates more than the front side of the leaf. And then it was observed that the young leaf transpirates more than the old leaf. The equipment can be successfully applied as point measurement for different plant types under different climatic condition. It can be concluded that, this measurement technique can be applied to an irrigated area and transpiration results can be used as a useful tool for planning of irrigation water requirement.

REFERENCES

1) Brutsaert, W. and Stricker, H. (1979). An advection-aridity approach to estimate actual regional evapotranspiration. *Water Resources Research*, 15(2), 443-450
2) Boast, C.W and Robertson, T. M. (1982) A micro-lysimeter method for determining evaporation from bear soil: description and laboratory evaluation. *Soil Sci. Soc. Am.J.*,46, 689-696
3) Penman, H.L. (1948). Natural evaporation from open water, bear soil and grass. *Proc. R. Soc.* London, Ser. A, 120-146
4) Monteith J.L., The development and extension of Penman's evaporation formula, in *Application of Soil Physics*, ed. By D. Hillel, Academic Press, Orlando, Fla., pp.247-253, 1980.
5) Watanabe, K.: Evaporation measurement for mapping the groundwater discharge on tunnel wall, Part 1: *J. of JSGE*, Vol. 30, pp.189-196, 1989.
6) Watanabe, K.: Evaporation measurement in ventilation drift, *Part 1: Stripa Technical Report*, pp.1-131, June 1991.
7) Watanabe, K.: Evaporation measurements in the Thammasat University, Rangsit campus, Tentative report, 2000.
8) Aye Aye Thant, Watanabe, K., Khanchai, C., Krittya, L. and Kyi Myint Thwin: Field measurement of transpiration from a mango tree, *Annual Conference of JSCE*, 2001.
9) Kyi Myint Thwin, Watanabe, K., Aye Aye Thant, Khanchai, C.: Transpiration measurement from plant leaf by using two-sensor type evaporation meter, *Annual Conference of JSCE*, 2001.
10) Ueda, M.: Measurement of the gradient of the water-vapor pressure and the diffusion coefficient, *Japan J. Applied Physics*, pp.144-149, 1956.

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