A Heat Balance Method for Measuring Water Flow Rate in Stems of Intact Plants and Its Application to Sugarcane Plants

By TETSUO SAKURATANI* and JIRO ABE**

* **Department of Physics and Statistics, National Institute of Agricultural Sciences**
(Yatabe, Ibaraki, 305 Japan)
** **Okinawa Branch, Tropical Agriculture Research Center**
(Maesato, Ishigaki, Okinawa, 907 Japan)

Introduction

In recent years, intense interest has been focused on attaining high water-use efficiency while maintaining high productivity, because of increasing competition for water with non-agricultural users and of increasing demand for the expansion of agricultural areas into marginal lands. For this purpose, the relations of transpiration of crops with environmental factors and dry matter production have been actively investigated.

One of the major problems in such investigation is how to estimate the transpiration rate of crops in the natural conditions. The chamber method, in which transpiring plants are covered by a tent or a box made of transparent materials, has been widely used. The direct measuring methods of transpiration stream in a plant stem in the natural condition have been also employed by some researchers. However, each method has important shortcomings. In the former, microclimate in the chamber differs from out-door conditions, and in the latter, it is difficult to obtain reliable values of water flux in a plant stem.

Sakuratani,[8] the senior author, devised a new method, on the basis of heat balance of a segment of plant, to determine more accurately the water flow rate in the stem of intact crop plants than by traditional methods. The new method has been successfully used to study effects of environmental factors on water flow in the stems of soybean,[11] cucumber,[9] sunflower,[8] tomato[3] and young popula.[3]

This paper describes the principle and apparatus of this method and results obtained by its application to sugarcane plants.

Theory

The new method is essentially a modification of the stem (or trunk) heat balance method which several workers[1,5,6,7] have used to detect water flow rate in the trunk of arbores or in the stem of herbaceous plants.

Consider a stem segment to which heat energy is continuously supplied. When steady conditions exist as to temperature in the segment, the heat energy supplied, Q W, should be equal to the heat loss due to conduction, convection and mass flow (Fig. 1).

$$Q=Q_f+q_u+q_d+q_s, \quad \cdots\cdots(1)$$

where Q_f is the energy transported by water flow in the stem from heat source [W], q_u and q_d the energy transferred upstream and downstream, respectively, by thermal conduction along the stem [W], and q_s the energy lost by the convection from the surface of the

Present address:
* Upland Farming Division, Kyushu National Agricultural Experiment Station (Miyakonojo, Miyazaki, 885 Japan)
** Second Agronomy Division, Tohoku National Agricultural Experiment Station (Higashianiwa, Morioka, 020 Japan)

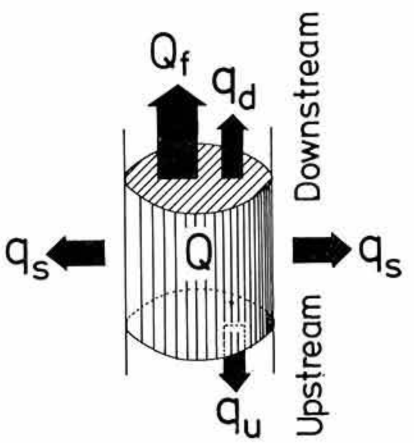

Fig. 1. Heat balance for a stem segment to which energy, Q, is supplied

heated stem into the surrounding air [W].

The energy transported by water flow is given by the following equation:

$$Q_f = cF(T_d - T_u), \quad \cdots\cdots(2)$$

where c is the specific heat of water [4.18 J $g^{-1}°C^{-1}$], F the rate of water flow in the stem [$g\,s^{-1}$], T_d the temperature of water flowing out of the segment and T_u the temperature of water streaming into the segment.

Combination of Eq. (1) with Eq. (2) yields the following relation for the water flow rate, equivalent to the amount of water moving up through cross-section of the stem per unit time:

$$F = \frac{Q - q_u - q_d - q_s}{c(T_d - T_u)}, \quad \cdots\cdots(3)$$

The values of q_u and q_d can be estimated from the next equation obtained on the basis of one-dimensional heat conduction in plant stem:

$$q_u = \lambda A \frac{T_u - T'_u}{\Delta x}, \quad q_d = \lambda A \frac{T_d - T'_d}{\Delta x}, \quad \cdots\cdots(4)$$

where λ is the thermal conductivity of the stem [$W\,m^{-1}K^{-1}$], A cross-sectional area of the heated segment [m^2], T'_u the temperature at Δx upstream of the measuring point of T_u and T'_d the temperature at Δx downstream of the measuring point of T_d [°C]. As a value of λ for most crops with high water content, we can use 0.54 $W\,m^{-1}°C^{-1}$ which is an average from soybean, cucumber, sugarcane and kidney bean plants.[10] The value of q_s is estimated by a cylindrical heat flow sensor attached around the heated segment.

Construction of apparatus

The apparatus for the heat balance method consists principally of a heat source mounted on stem segment, a heat flow sensor and thermometers (Fig. 2). As the heat source, a 0.1 or 0.14 mm silk-insulated Manganin wire is closely wound around the stem with a width which is equal to or two times larger than the diameter of the stem. The Manganin wire of 0.1 mm in diameter is used for thin stem of 0.5–1.0 cm in diameter while a 0.14 mm-diameter-wire is applied to the stem of 1.0–

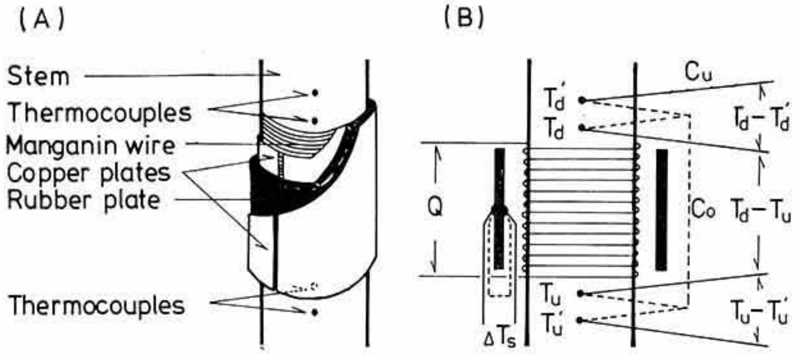

Fig. 2. Apparatus for measuring the water flow rate in plant stem (A) and its setup (B)

3.0 cm in diameter. The heat source is fed continuously by DC-current with a constant voltage. The heat energy, Q, supplied to the stem segment is evaluated by

$$Q = IE, \quad \cdots\cdots(5)$$

where I and E are the electric current [A] and voltage of DC-electric source [V], respectively.

The heat flow sensor for detecting q_s is made so as to fit the circumference of the heat source. It consists of a thin plate of soft rubber having thermal conductivity of 0.13 W $m^{-1}{}^{\circ}C^{-1}$ and thickness of 1.0 or 2.0 mm and soft annealed copper plates of 0.08 mm in thickness which applied on the inside and outside of the rubber plate to maintain the uniform temperature distribution on the surfaces of the rubber plate. The heat flow from the inside of the sensor to the outside is estimated from the equation:

$$q_s = k\Delta T_s, \quad \cdots\cdots(6)$$

where k is a coefficient related to the thermal conductivity of the rubber and to the shape and size of the sensor [W $^{\circ}C^{-1}$], and ΔT_s the temperature difference between the inside and outside of the sensor. The temperature difference, ΔT_s, is measured by enameled copper-constantan thermocouples of 0.1 mm in diameter fixed on the each side of the copper plates.

The magnitude of k can be determined by the following equation derived from Eqs. (3) and (6) when $F = 0$:

$$k = \frac{Q - q_u - q_d}{\Delta T_s}, \quad \cdots\cdots(7)$$

The condition of $F = 0$ can be made by cutting the plant stem immediately above and below the position at which the apparatus is set. If water flow rate is null or very little as observed at pre-dawn or nighttime, the value of k is possibly determined without cutting the stem.

The temperature difference, $T_d - T_u$, $T_u - T'_u$ and $T_d - T'_d$ in Eqs. (3) and (4) are measured with thermocouples consisting of copper and constantan wires with diameter of 0.1 mm. Thermocouples for measurements of T_u and T_d are attached by a small amount of adhesive agent, respectively to the positions of 1.0 mm up and 1.5–2.0 mm downward the heated segment, in order to avoid direct influences of the heat source. Thermocouples for T'_d and T'_u are also attached to the positions of 2.0 mm upward and downward each thermocouple, respectively for T_d and T_u. Those thermocouples are wired with each other so that the temperature difference in Eqs. (3) and (4) are directly detected (Fig. 2B).

The electric signals corresponding to the temperature difference are of order of 1–100 μV. Thus the signals should be recorded through a low-noise amplifier on a multichannel automatic recorder. The apparatus set on the surface of plant stem must be usually completely covered by heat insulator consisting of sponge rubber and aluminum foil to minimize the thermal perturbation due to the ambient environment.

Accuracy of apparatus

The accuracy and reliability of the apparatus were tested by comparing the water flow rates of soybean, sunflower and tomato plants measured by this apparatus with the transpiration rates obtained by the weighing method.[8,10] The results showed that the new apparatus can determine the water flow rate in a relatively thin plant stem with higher water flux with an accuracy of the order of ±10%.

Application of apparatus to sugarcane plants

1) Materials and methods

Diurnal change in transpiration rate of sugarcane plants, substantially equivalent to the water flow rate in the stem, was investigated using the new method. The experiment was conducted at Okinawa Branch, Tropical Agriculture Research Center, Ishigaki, the southernmost part of Japan from September 25 to October 4, 1979.

As the test plants, we used four individuals selected equally from each plant community of cv. NCo310 and cv. F161 growing, respectively, in a plot of approximately 200 m². The stem diameters of the materials ranged from 2.0 to 3.4 cm. The measurements of transpiration rate were made using a stalk of each individual. The apparatus as described in Fig. 2 was attached to the surface of the internode at about 50 cm above the ground surface.

In the present study, T'_u and T'_d were not measured by assuming that q_u and q_d should be much smaller than Q_f transported by the water flow in plant stem. However, later error analysis indicated that the neglect of q_u and q_d lead to noticeable error for plants with thick stem such as sugarcane. Therefore, (q_u+q_d) was roughly estimated from the following equation obtained empirically:

$$(q_u+q_d)=K(T_u+T_d), \quad \cdots\cdots(8)$$

where K is a proportional coefficient. The value of K was determined by deviding the value of $(Q-q_s)$ by the value of (T_u+T_d) which were obtained at pre-dawn when the water flow rate could be substantially assumed to be null or very little.

Soil moisture tension near the test plants was measured with mercury tentiometers positioned vertically in the soil of 20 cm.

To investigate the effects of irrigation on sugarcane, we watered the two test plants of NCo 310 at 0900 JST on October 4. The amount of water supplied was equivalent to water depth of 30 mm.

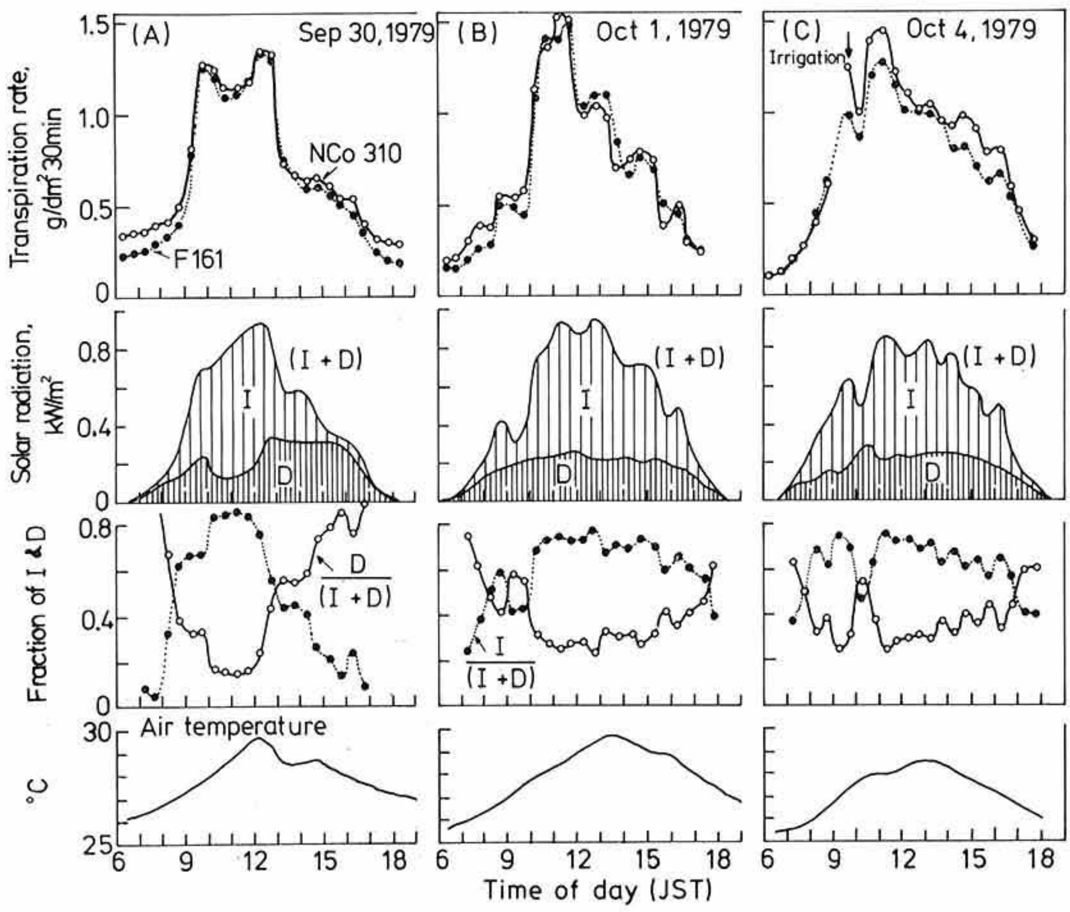

Fig. 3. Diurnal march of transpiration rate of field-grown sugarcane plants, solar radiation components and air temperature on fair days
(I+)=total short-wave radiation, I=direct short-wave radiation,
D=diffuse short-wave radiation.

Solar radiation data used for analyses in the present study were the data collected routinly at the Okinawa Barnch as a part of the special research project on more efficient utilization of natural energy for agricultural production organized in the Ministry of Agriculture, Forestry and Fisheries of Japan. Air temperature measurements taken routinly at the observation field were also used.

2) Results and discussion

Fig. 3 shows the diurnal changes in the measured transpiration rate (average of two individuals), the components of total short-wave radiation and air temperature for fair days. The soil moisture tention at 20 cm depth in non-irrigated plot for these days ranged between 2.6 and 2.8. As can be seen in Fig. 3-(A) and -(B), there is no significant varietal difference in the transpiration rate between the two cultivars.

Although the diurnal patters in total short-wave radiation, $(I+D)$, for the three days were substantially symmetrical, unsymmetrical were these in the transpiration rate. The transpiration rates increased progressively from sunrise to around 0900 JST, subsequently increased drastically and reached a peak at 1100–1200 JST. The magnitude of the peak was 1.3, 1.5 (average of the two cultivars) and 1.3 (F161) g dm^{-2} 30 min^{-1} for September 30, October 1 and 4, respectively. After that, as can be seen clearly in Fig. 3-(B) and -(C), the transpiration rates began decreasing prior to the decrease of total short-wave radiation. Such change was also observed for the irrigated sugarcane plants (Fig. 3-C), despite of the facts that the soil moisture tension was reduced from 2.7 to 1.4 and the level of transpiration rate was raised by 13% (average in 0930–1830 JST) by the irrigation conducted at 0900 JST. The diurnal patterns in the transpiration of sugarcane described above agreed approximately with a previous report.[2]

A dip is formed in the transpiration curve during 1000 to 1230 JST period on September 30. During this period, the ratio of diffusive radiation, D, to total short-wave radiation, $(I+D)$, reduced from 33% at 0930 JST to 15% at 1100 JST and then increased to reach a value of 38% at 1230 JST, whereas total short-wave radiation increased gradually. It is reported that weak diffuse light results in a partial close of the stomata of sugarcane.[2] Kuroiwa[4] indicated that total stand photosynthesis rate for diffuse radiation is generally higher than that for direct radiation. Apparently, the passing reduction of the transpiration rate which occurred at midday on September 30 was owing to that of diffuse radiation.

Conclusion

The newly developed apparatus can measure the absolute value of water flow in an intact plant stem with acceptable error, and is fairly sensitive to the change of water flow rate in the stem as shown in the present experiment.

However, the apparatus has still the following two points to be solved. The first is that setting of the apparatus around a plant stem takes 20 to 30 min under field conditions. The second is that the long time fixation of the sensing element on a plant stem arrests inevitably the radial growth of the plant stem. Recently, the apparatus has been improved so that it is flexible and can be easily set and removed to/from a plant stem.[10] This apparatus may stimulate wider application of the stem heat balance method modified by us.

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