AIR HUMIDITY WITHIN BOUNDARY LAYER OF A TRANSPIRING LEAF : I. RELATIONSHIP BETWEEN TRANSPIRATION AND WATER VAPOR DENSITY AT LEAF SURFACE

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AIR HUMIDITY WITHIN BOUNDARY LAYER OF A TRANSPIRING LEAF I. RELATIONSHIP BETWEEN TRANSPIRATION AND WATER VAPOR DENSITY AT LEAF SURFACE

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KITANO M. and EGUCHI H. *Air humidity within boundary layer of a transpiring leaf. I. Relationship between transpiration and water vapor density at leaf surface.* BIOTRONICS **16**, 39–45, 1987. A simple system for on-line measurement of water vapor density within leaf boundary layer was developed, and water vapor density (W_{BO}) at the cucumber leaf surface was analyzed in relation to transpiration rate (E). In the system, air near the leaf surface was sampled continuously through a capillary tube (ϕ0.4 mm) and drawn into a sampling capsule (1.2 cm^3 in volume) by using an air pump. Temperature and relative humidity of the sampled air were measured by a T-thermocouple (ϕ0.1 mm) and a small sized humidity sensor of an electric capacitance meter (4 mm$\times$ 6 mm$\times$0.2 mm) installed in the sampling capsule, respectively. Water vapor density of the sampled air was calculated from the air temperature and relative humidity measured. The system was reliable for understanding dynamics of transpired water vapor in leaf boundary layer and humidity condition to which leaf is exposed directly: W_{BO} was higher than water vapor density (W_A) of ambient air outside the boundary layer and varied with E as affected by evaporative demand and stomatal movement. $W_{BO}-W_A$ was directly proportional to E, and the proportionality was dependent on characteristics of air current and the sampling position of the W_{BO} measurements.

Key words: *Cucumis sativus* L.; cucumber leaf; humidity boundary layer; transpiration; evaporative demand; stomatal movement.

INTRODUCTION

Leaf is surrounded by leaf boundary layer. Across the boundary layer, transpired water vapor is transferred to ambient air. The boundary layer is moistened with the transpired water vapor, and air humidity near the leaf surface seems to vary with transpiration. On the other hand, humidity is one of important environmental factors which affect evaporative demand and stomatal movement. So, it is important to measure humidity within the boundary layer of the leaf. For such measurement, highly complex systems such as a microwave refractometer (*3, 4*), an infrared psychrometer (*10*) and a mass spectrometer (*6*) have been used. Humi-

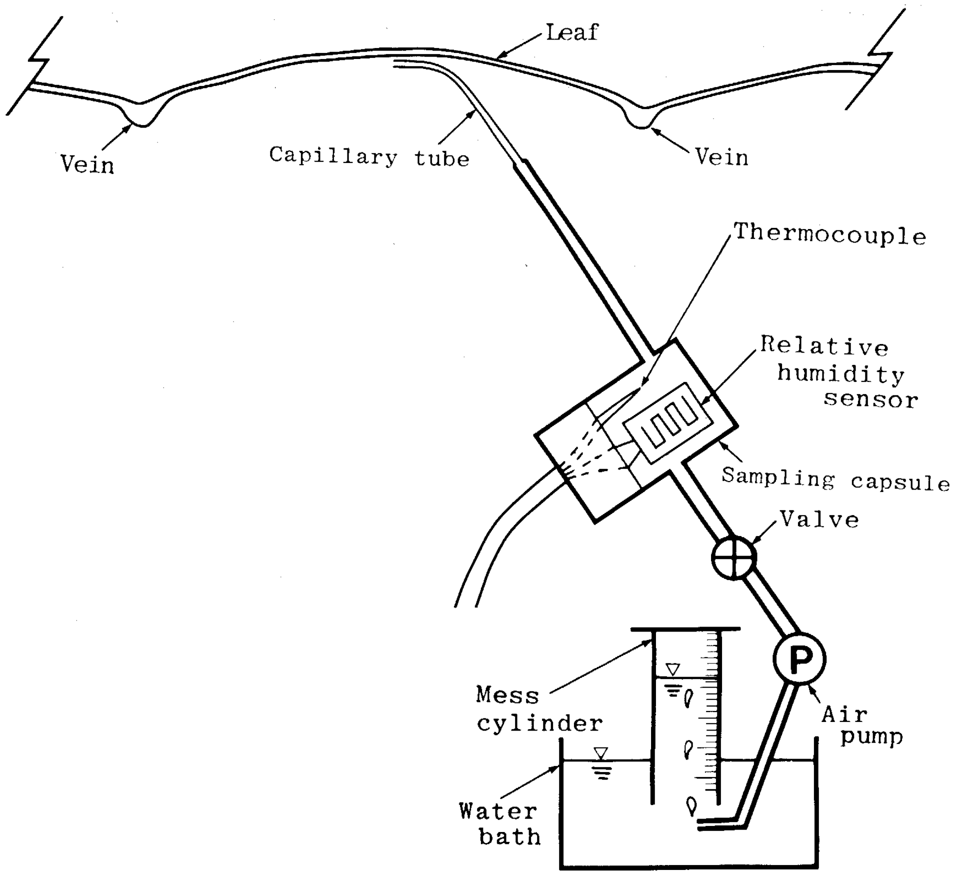

Fig. 1. Schematic diagram of measuring system of water vapor density in leaf boundary layer.

dity in the boundary layer, however, has not been analyzed enough in relation to transpiration as affected by evaporative demand and stomatal movement.

The present paper deals with analysis of water vapor density at leaf surface in relation to transpiration by using a simplified system developed for measuring water vapor density within leaf boundary layer.

MATERIALS AND METHODS

Leaf material

Cucumber plants (*Cucumis sativus* L. var. Hort. Chojitsu-Ochiai) were used in the experiment. The plants were potted in Vermiculite moistened with nutrient solution and grown at air temperature of 23°C and relative humidity of 70% in a phytotron glass room. The intact 3rd leaf at 5 leaves stage was used as a specimen, which was about 20 cm in characteristic length.

Measurements

Water vapor density (W_{BO}, g m^{-3}) at leaf surface, transpiration rate (E, mg cm^{-2} min^{-1}) and leaf temperature (T_L, °C) were examined in the phytotron glass room and an artificial light growth chamber, where the leaf was fixed horizontally by supporting fine threads. Figure 1 shows the system for measuring water vapor density within the boundary layer. By using a small air pump, air in the boundary layer was sampled continuously through a capillary tube of stainless steel and drawn into a sampling capsule. The capillary tube was 0.4 mm in inside diameter and 0.7 mm in outside diameter. For measuring W_{BO}, the capillary tube was kept in contact with leaf surface at a sampling position which was a flat part between prominent veins and about 4 cm apart from the windward of the center of leaf. So, W_{BO} can be considered to indicate water vapor density at the position 0.35 mm apart from the leaf surface, because of 0.7 mm in the outside diameter of the capillary tube. The sampling capsule was a cylinder with inside diameter of 10 mm and volume of 1.2 cm^3. In the capsule, a T-thermocouple (ϕ 0.1 mm) and a small sized humidity sensor (4 mm $\times$ 6 mm $\times$ 0.2 mm) were installed for measuring temperature (T_{AC}, °C) and relative humidity (RH_C, %) of the sampled air. The thermocouple had the accuracy of 0.1°C and the time constant of about 1 sec. The humidity sensor was an electric capacitance meter (HMP 15, Vaisala Oy) of which electric capacitance varies with relative humidity of surrounding air. This sensor had the accuracy within 3% and the time constant of about 1 sec, which was reliable in static and dynamic characteristics (*8*). The sensor signals of T_{AC} and RH_C were transmitted to CPU through interfaces, and W_{BO} was calculated in on-line by the following equation (*9*),

$$W_{BO}=\frac{RH_C}{100}\times 1323.0\ \exp\{17.269T_{AC}/(237.3+T_{AC})\}/(273.16+T_{AC}) \quad (1)$$

The sampling rate of air, volume of the sampling capsule and characteristics of the sensors were responsible for dynamic characteristics of this measuring system. By adjusting the valve of air sampling path, sampling rate of air was set at about 2 cm^{3}min^{-1}, which corresponds to air velocity of about 0.3 m s^{-1} at the nozzle of the capillary tube. At this sampling rate, the time constant of the system was about 1 min. W_{BO} measured at the surface of a wetted filter paper by this sampling method was almost saturated with water vapor. This fact indicates that this sampling method does not disturb the air current near the leaf surface.

On the other hand, E was measured by weighing the plant and pot in which the pot surface was sealed with polyethylene film to prevent the evaporation: E was sum of transpiration rate (E_{AD}) in adaxial surface and transpiration rate (E_{AB}) in abaxial surface. For measuring T_L, the thermocouple (ϕ 0.1 mm) was inserted into the mesophyll, where the thermocouple generated reliable signals of leaf temperature without disturbances by radiation and ambient air. Environmental factors of temperature (T_A, °C) and relative humidity (RH_A, %) of ambient air outside the boundary layer and short wave radiant flux density (R_S, kW m^{-2}) were measured by the respective sensors of the thermocouple, the electric capacitance meter and an Eppley pyranometer. Water vapor density (W_A, g m^{-3}) of ambient air outside the boundary layer was obtained by suing Eq. (1), where T_A and RH_A were substituted for T_{AC} and RH_C, respectively.

Table 1. Diurnal variations of water vapor density (W_{BO}) at abaxial leaf surface, transpiration rate (E) and leaf temperature (T_L) responding to short wave radiant flux density (R_S) of solar radiation under different weather conditions in the phytotron glass room where controlled ambient air (air temperature of 23°C and water vapor density of 14 g m^{-3}) flowed upward with velocity of 0.3 m s^{-1}.

Date	Time of day (h)	R_S (kW m^{-2})	W_{BO} (g m^{-3})	E (mg cm^{-2} min^{-1})	T_L (°C)
	0	0.00	16.5	0.02	22.2
	2	0.00	16.7	0.04	21.4
	4	0.00	16.7	0.05	21.2
	6	0.01	17.6	0.08	20.8
	8	0.14	20.9	0.18	23.5
May 24, 1986	10	0.26	25.3	0.32	26.4
(fair day)	12	0.44	28.0	0.40	30.0
	14	0.60	32.2	0.47	31.0
	16	0.24	22.9	0.22	26.0
	18	0.03	19.8	0.09	22.9
	20	0.00	17.4	0.06	22.4
	22	0.00	16.8	0.04	22.2
	0	0.00	16.6	0.05	21.9
	2	0.00	16.5	0.04	21.9
	4	0.00	16.8	0.05	21.5
	6	0.00	17.5	0.09	21.0
	8	0.01	18.0	0.10	20.8
May 29, 1986	10	0.05	18.7	0.13	21.4
(rainy day)	12	0.08	19.6	0.15	22.1
	14	0.03	18.7	0.13	21.1
	16	0.03	18.9	0.12	21.6
	18	0.01	18.9	0.09	21.6
	20	0.00	17.1	0.05	22.1
	22	0.00	16.7	0.04	22.0

RESULTS AND DISCUSSION

In the phytotron glass room, W_{BO} at abaxial leaf surface, E and T_L were examined in relation to R_S under different weather conditions, where controlled ambient air flowed upward with a velocity (V, m s^{-1}) of 0.3 m s^{-1} at T_A of 23°C and W_A of 14 g m^{-3}. Table 1 shows diurnal variations of W_{BO}, E, T_L and R_S on a fair day and a rainy day. W_{BO} was affected by R_S and clearly different from W_A. In nighttime, W_{BO} was almost constant at about 17 g m^{-3} which was about 3 g m^{-3} higher than W_A. In daytime, W_{BO} varied at higher elevation even under constant W_A, and W_{BO} was nearly equal to saturation vapor density at T_L: W_{BO} on the fair day was remarkably higher than that on the rainy day and the difference in W_{BO} between those days reached to 10 g m^{-3}. E and T_L in day time were also affected by R_S and remarkably higher on the fair day than the rainy day; at 14 h, E was about 3.5-fold higher, and T_L was about 10°C higher. On the relationships among E, T_L and R_S, the authors (*1*) have reported that water vapor density (W_L, g m^{-3}) of leaf

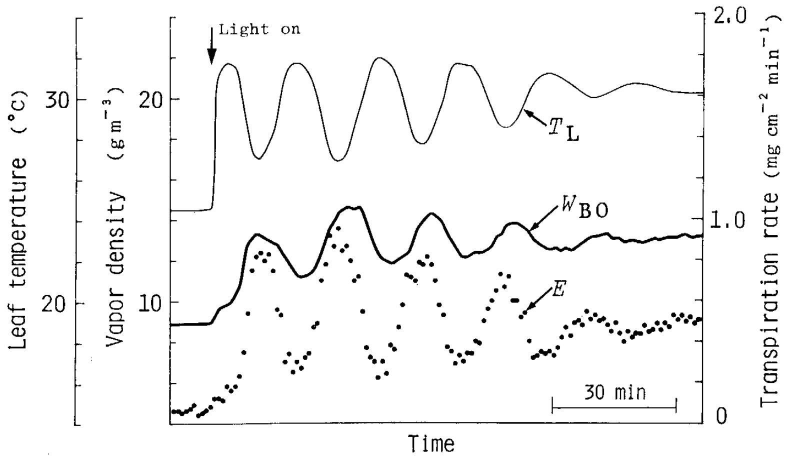

Fig. 2. Variations of water vapor density (W_{BO}) at abaxial leaf surface, transpiration rate (E) and leaf temperature (T_L) under tungsten light at short wave radiant flux density of 0.56 kW m^{-2} in the growth chamber, where controlled ambient air (air temperature of 25°C and water vapor density of 8 g m^{-3}) flowed laterally with velocity of 0.7 m s^{-1}.

intercelluler space (*2*) varies with T_L affected directly by R_S, and E in daytime relates linearly to $W_L - W_A$ which is responsible for evaporative demand against leaf. The variation of W_{BO} observed in this experiment appeared in the pattern similar to those of E and T_L. However, it is necessary to examine whether W_{BO} is directly affected by E or W_{BO} varies with W_L; in this experiment, the variation of W_{BO} was analyzed under the condition where T_L and W_L decrease with increasing E by transpirational cooling effect. Figure 2 shows variations of W_{BO} at abaxial leaf surface, E and T_L under constant tungsten light at short wave radiant flux density of 0.56 kW m^{-2} in the growth chamber where controlled ambient air flowed laterally with V of 0.7 m s^{-1} at T_A of 25°C and W_A of 8 g m^{-3}. After the time when the light was turned on, stomatal oscillation was induced by drastic change in evaporative demand (*7*), and W_{BO}, E and T_L oscillated with a period of 20 min even under constant T_A, W_A and R_S. W_{BO} and E synchronized with each other, but T_L did not synchronize with W_{BO}, and there was phase difference of half a period between W_{BO} and T_L. This indicates that W_{BO} depends directly on E without influence of W_L varying with T_L. Thus, W_{BO} varied with transpiration rate which was affected by stomatal movement even under constant air condition.

From an analogue of Ohm's law, water vapor flux density can be expressed by resistance for water vapor transfer and difference in water vapor density between leaf surface and outside of boundary layer. So, E_{AD} and E_{AB} can be written by

$$E' = 6 \times 10^{-2} \frac{W_{BO} - W_A}{r_{BO}} \tag{2}$$

where E' (mg cm^{-2} min^{-1}) is E_{AD} for adaxial surface or E_{AB} for abaxial surface, r_{BO} (s cm^{-1}) is resistance for water vapor transfer from leaf surface (sampling position for W_{BO} measurement) to ambient air and 6×10^{-2} is proportionality constant

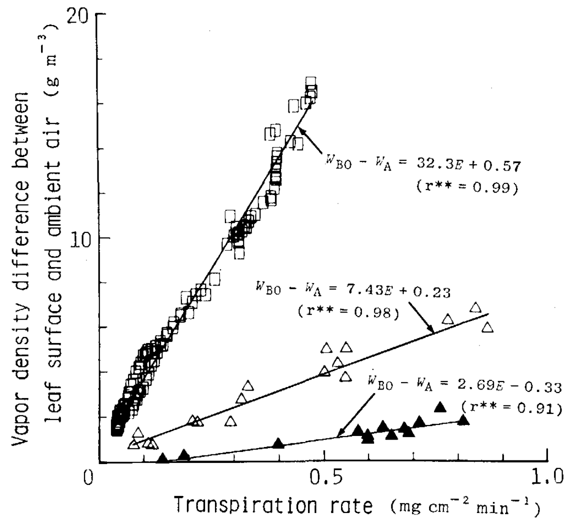

Fig. 3. Relationship between vapor density difference (W_{BO}–W_A) and transpiration rate (E): □, abaxial leaf surface exposed to upward air current with a velocity of 0.3 m s^{-1} in the phytotron glass room; △ and ▲, abaxial and adaxial leaf surfaces exposed to lateral air current with a velocity of 0.7 m s^{-1} in the growth chamber, respectively; W_{BO}, water vapor density at leaf surface; W_A, water vapor density of ambient air outside the boundary layer; r**, correlation coefficient significant at 1% level.

determined by the used units.

Therefore, relationship between $W_{BO}-W_A$ and E (sum of E_{AD} and E_{AB}) can be written by

$$W_{BO}-W_A=A\times B\times E \tag{3}$$

with

$$A=\frac{r_{BO}}{6\times 10^{-2}} \quad \text{and} \quad B=\frac{E'}{E}=\frac{E_{AD}}{E} \quad \text{or} \quad \frac{E_{AB}}{E} \tag{4}$$

where parameter A mainly depends on characteristics of air current within the boundary layer and parameter B represents relative intensity of E_{AD} and E_{AB}.

In quasi-steady state where time constant of the measuring system (about 1 min) was remarkably smaller as compared with the dynamics of W_{BO}, the relationship between $W_{BO}-W_A$ and E was examined under the respective conditions in the phytotron glass room and the artificial light growth chamber described above. Figure 3 shows dependence of $W_{BO}-W_A$ on E in the abaxial and adaxial surfaces. In all cases, there was high correlation (r**>0.9) between $W_{BO}-W_A$ and E, and the regression lines passed nearly to the origin (0). So, the regression coefficients in the respective lines can be considered to be approximately the product of A and B in Eq. (3). The regression coefficient in abaxial surface was 32.2 in the phytotron glass room and 7.43 in the growth chamber. This larger regression coefficient in the phytotron glass room indicated that the parameter A, i.e. r_{BO}, in the phytotron glass room was remarkably larger than that in the growth chamber: The transpired water vapor was swept away (*5*) from the leaf surface in the lateral air current with V of 0.7 m s^{-1} in the growth chamber more easily than in the upward air current with V of 0.3 m s^{-1} in the phytotron glass room. Furthermore, the regression coefficient in the growth chamber was 7.43 in abaxial surface and 2.69 in adaxial surface. This smaller coefficient in adaxial surface was considered to be attributed mainly to the parameter B, i.e. E'/E, in adaxial surface smaller than that in abaxial surface : Stomatal frequency in adaxial surface was remarkably lower than that in abaxial surface (the ratio of stomatal frequency in adaxial surface to that in abaxial surface was 1: 1.8), and E_{AD} was supposed to be lower than E_{AB}. Furthermore, this direct proportionality between $W_{BO}-W_A$ and E indicates that the developed system could be also applicable as a simple tool for evaluation of transpiration rate in a small part of leaf.

From the results, it could be conceivable that humidity at leaf surface varies with transpiration rate as affected by evaporative demand and stomatal movement, and stomatal complexes in leaf epidermis are exposed directly to the humidity different from that of ambient air.

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