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AIR HUMIDITY WITHIN BOUNDARY LAYER OF A TRANSPIRING LEAF
II. PROFILE OF WATER VAPOR DENSITY WITHIN THE BOUNDARY LAYER

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KITANO M. and EGUCHI H. *Air humidity within boundary layer of a transpiring leaf. II. Profile of water vapor density within the boundary layer.* BIOTRONICS **16**, 47–55, 1987. Profile of water vapor density near the cucumber leaf surface was examined in comparison with air temperature profile in relation to effects of air current and stomatal responses to environment. Profile of water vapor density was different from air temperature profile. The difference was estimated to be caused by stomatal and cuticular resistances for transpiration and appeared in the large gap of water vapor density at leaf surface. Furthermore, differences were found between profiles on adaxial and abaxial surfaces, which were considered to be caused by more turbulent air current and higher transpiration rate on abaxial leaf surface. Air conditions such as temperature, saturation vapor deficit and wind velocity of ambient air outside the boundary layer affected the profile of water vapor density, and these effects of air conditions closely related to stomatal responses which made the stomatal resistance higher at the lower air temperatures, the higher saturation deficits and the higher wind velocities.

Key words: *Cucumis sativus* L.; cucumber leaf; leaf boundary layer; humidity profile; temperature profile; transpiration; stomatal response.

INTRODUCTION

Momentum, heat and mass are transferred from leaf to ambient air across leaf boundary layer. The characteristics of transferring depend on boundary layer resistance and on the respective gradients of wind velocity, air temperature and mass concentration near the leaf surface. To elucidate the characteristics of air current within the leaf boundary layer, Yabuki and Nishioka (*8*) and Grace and Wilson (*3*) measured wind velocity profile near the leaf surface. The stomatal and cuticular resistances as well as the boundary layer resistance are the important factors responsible for the transpiration. Stomatal complexes in the leaf epidermis are directly exposed to humidity gradient near the leaf surface, which drives water vapor transferring from the leaf, and the water loss of the leaf by transpiration closely relates to stomatal responses through water balance of the leaf. So, it is essential to examine humidity profile near the leaf surface in relation to effects of air current and stomatal responses.

For such purpose, the present paper deals with analysis of profile of water vapor density near the leaf surface by applying the measuring method reported in the previous paper (*5*).

MATERIALS AND METHODS

Leaf materials

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 of the healthy plant at 5 leaves stage was used as a specimen which was about 20 cm in characteristic length. Furthermore, an artificial leaf of a wetted filter paper and an ABA treated leaf which was the 3rd leaf sprayed with abscisic acid (10^{-4}M), were also used.

Measurements

The leaf was fixed horizontally by supporting fine threads in an artificial light growth chamber, where controlled ambient air outside the boundary layer flowed laterally. Profiles of water vapor density (W_{Bi}, g m^{-3}) and air temperature (T_{Bi}, °C) near the leaf surfaces were examined under different temperatures (T_A, °C), saturation vapor deficits (*SVD*, g m^{-3}) and wind velocities (V, m s^{-1}) of ambient air outside the boundary layer. For measuring W_{Bi}, the method developed by the authors (*5*) was used. In the system, air near the leaf surface was sampled continuously through a capirally tube (0.4 mm in inside diameter). W_{Bi} was measured continuously in a sampling capsule (1.2 cm^3 in volume) by using a T-thermocouple (ϕ0.1 mm copper-constantan) and a small sized humidity sensor (4 mm$\times$6 mm$\times$ 0.2 mm) of an electric capacitance meter (HMP 15, Vaisala Oy). T_{Bi} was measured by the thermocouple (ϕ0.1 mm) attached at the nozzle of the capirally tube.

At the first step, the capirally tube was kept in contact with the leaf surface at a sampling position which was between prominent veins and about 4 cm apart from the windward of the center of leaf. Then, W_{Bi} and T_{Bi} measured at the surface were defined as W_{BO} and T_{BO}, respectively: It was considered that W_{BO} and T_{BO} can indicate W_{Bi} and T_{Bi} at the position 0.35 mm apart from the leaf surface, because of 0.7 mm in the outside diameter of the capirally tube. Leaf temperature (T_L, °C) was measured by the thermocouple (ϕ0.1 mm) inserted into the mesophyll, and water vapor density (W_L, g m^{-3}) of the leaf intercelluler space was treated as the saturation vapor density at T_L; W_L and T_L in the experiment were regarded as water vapor density and temperature at the position 0 mm apart from leaf surface, respectively. In steady state, the capirally tube was set at different vertical positions distancing from the leaf surface, and the profiles of W_{Bi} and T_{Bi} near the leaf surface were examined. Environmental factors of T_A, relative humidity (RH_A, %), V and short wave radiant flux density (R_S, kW m^{-2}) were measured by the respective sensors of the thermocouple, the electric capacitance meter, a hot wire anemometer and an Eppley

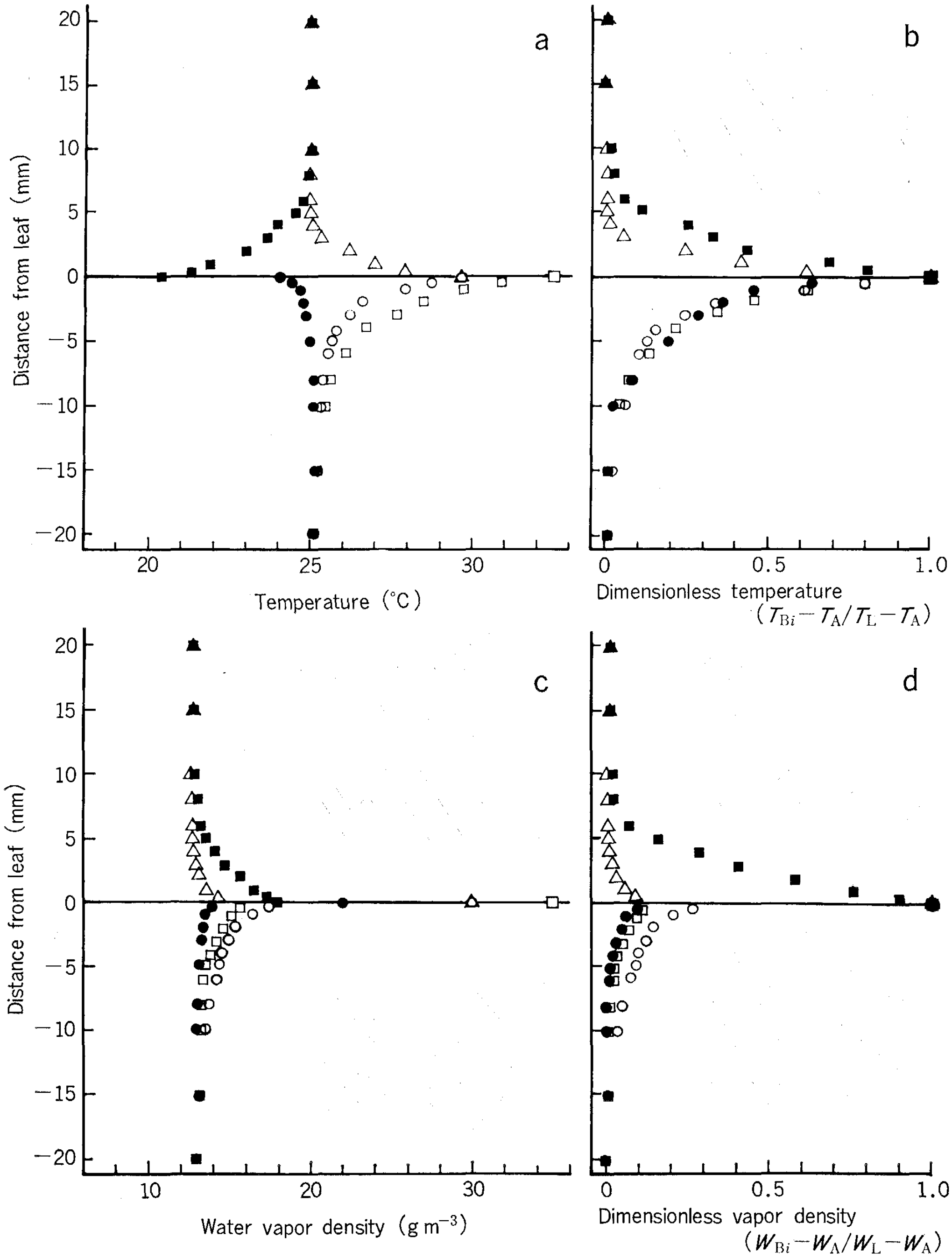

Fig. 1. Profiles of temperature (a), dimensionless temperature (b), water vapor density (c) and dimensionless vapor density (d) of air near the surface of the various materials at temperature of 25°C, saturation deficit of 10 g m^{-3} and lateral wind velocity of 0.7 m s^{-1} of ambient air outside the boundary layer: ○, abaxial surface of a cucumber leaf under the tungsten light; ●, abaxial surface of a cucumber leaf in darkness; □, abaxial surface of a cucumber leaf treated with 10^{-4} M ABA under the tungsten light; △, adaxial surface of a cucumber leaf under the tungsten light; ■, adaxial surface of a wetted filter paper in darkness; T_{Bi}, air temperature near the leaf surface; T_A, temperature of ambient air outside the boundary layer; T_L, leaf temperature; W_{Bi}, water vapor density of air near the leaf surface; W_A, water vapor density of ambient air outside the boundary layer; W_L, water vapor density in the leaf.

pyranometer. *SVD* and water vapor density (W_A, g m^{-3}) of ambient air outside the boundary layer were calculated from the measured T_A and RH_A by the same method in the previous paper (*5*).

Furthermore, according to the usual practice in boundary layer theory (*7*), dimensionless vapor density and dimensionless temperature were defined as $W_{Bi}-W_A/W_L-W_A$ and $T_{Bi}-T_A/T_L-T_A$, respectively. Profiles of these dimensionless vapor density and temperature were also examined as well as profiles of W_{Bi} and T_{Bi}.

RESULTS AND DISCUSSIONS

Figure 1 shows profiles of T_{Bi}, $T_{Bi}-T_A/T_L-T_A$, W_{Bi} and $W_{Bi}-W_A/W_L-W_A$ at T_A of 25°C, *SVD* of 10 g m^{-3} and V of 0.7 m s^{-1} near the surface of the various materials; adaxial surface of the wetted filter paper in darkness, adaxial and abaxial surfaces of the cucumber leaf radiated by the tungsten light at R_S of 0.56 kW m^{-2}, abaxial surface of the cucumber leaf in darkness and abaxial surface of the ABA treated cucumber leaf under the tungsten light. The distinct differences were found in T_L and in profile of T_{Bi} among the various materials. T_L of the cucumber leaves under the light were remarkably higher than T_A, where T_L of the ABA treated leaf was about 3°C higher than T_L of the untreated leaf. On the other hand, each T_L of the wetted filter paper and the leaf in darkness was about 5°C and 1°C lower than T_A, respectively. Even in the case of large difference in T_L-T_A among the surfaces, the profiles of $T_{Bi}-T_A/T_L-T_A$ on the respective abaxial surfaces were almost similar to each other. Thus, influence of the buoyancy proportional to T_L-T_A on air current within the boundary layer was scarcely found in this experiment, where the ambient air current outside the boundary layer had Reynolds number of 0.9×10^4 and turbulence intensity of about 10%. On the other hand, the profile of $T_{Bi}-T_A/T_L-T_A$ on adaxial surface was different from that on abaxial surface: The profile on abaxial surface was similar to that in the turbulent boundary layer, and the profile on adaxial surface was similar to that in the laminar boundary layer. Yabuki and Nishioka (*8*) have indicated in the profile of wind velocity that the boundary layer on the flat adaxial surface of a cucumber leaf remains laminar at Reynolds number within 1×10^4 and turbulence intensity of 5 to 8%. In this experiment, the boundary layer on the adaxial surface was also seemed to be laminar, but the boundary layer on the abaxial surface was seemed to be turbulent rather than laminar, because prominent veins had effect of tripping of the air current near the abaxial surface which curved slightly upward between the prominent veins.

Clear differences among the respective surfaces of various materials were found also in thickness of the boundary layer: Thickness of temperature boundary layer was about 5 mm on adaxial surface of the cucumber leaf, 10 mm on the wetted filter paper and 15 mm on the abaxial surfaces of the cucumber leaves, respectively. This difference in thickness was considered to be brought by topographic features of the surface structure. Thickness of humidity boundary layer on each surface was nearly equal to that of temperature boundary layer, but profiles of humidity boundary layer was remarkably different from those in temperature boundary layer. There were large gaps between W_L and W_{BO} at the surfaces of cucumber leaves.

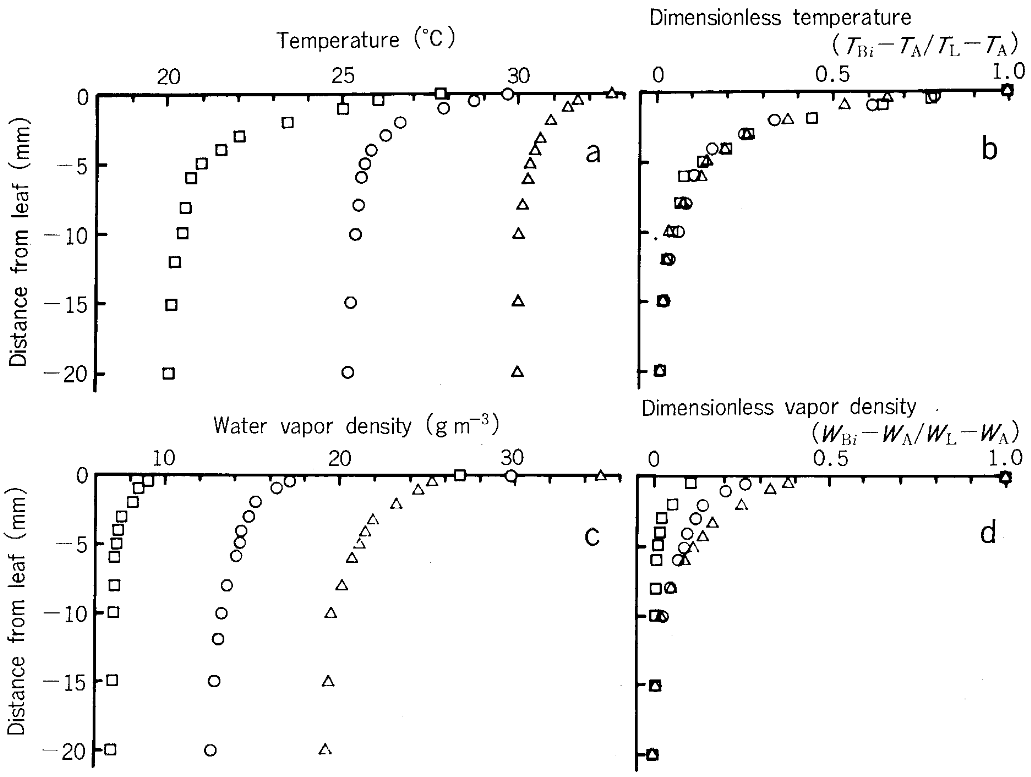

Fig. 2. Profiles of temperature (a), dimensionless temperature (b), water vapor density (c) and dimensionless vapor density (d) of air near the abaxial surface of a cucumber leaf under the tungsten light at respective temperatures of 20 (□), 25 (○) and 30°C (△) at constant saturation deficit of 10 g m^{-3} and lateral wind velocity of 0.7 m s^{-1} of ambient air outside the boundary layer (W_{Bi}, W_A, W_L, T_{Bi}, T_A, and T_L are explained in Fig. 1).

Grace *et al.* (*2*) have defined the difference in vapor pressure between leaf intercellular space and leaf surface as the *effective* vapor pressure deficit. In this experiment, W_L-W_{BO} was used as the *effective* vapor density deficit (*EVDD*). Percentage of *EVDD* to W_L-W_A remained at 75% on the abaxial surface of the leaf under the light and reached to 90% on other surfaces of the untreated and ABA treated leaves. On the other hand, *EVDD* was remarkably small on the surface of wetted filter paper, as well as small T_L-T_{BO} in the temperature profiles. These facts suggest that the large *EVDD* found in the cucumber leaves is attributed to high resistances of stomata and cuticular to vapor transfer: The vapor transfer from the wetted filter paper was affected by the boundary layer resistance only. The authors (*5*) have reported that $W_{BO}-W_A$ is directly proportional to transpiration rate. Among surfaces of the leaves, $W_{BO}-W_A$ was found to be largest under the light and smallest in darkness. $W_{BO}-W_A$ on abaxial surface of the ABA treated leaf with suppressed stomatal transpiration (*4*) was intermediate between the largest and the smallest values in the untreated leaf. $W_{BO}-W_A$ on adaxial surface remained at 30% of the largest $W_{BO}-W_A$. This smaller $W_{BO}-W_A$ on adaxial surface was considered to be caused by the transpiration rate lower than that on abaxial surface (*5*). Thus,

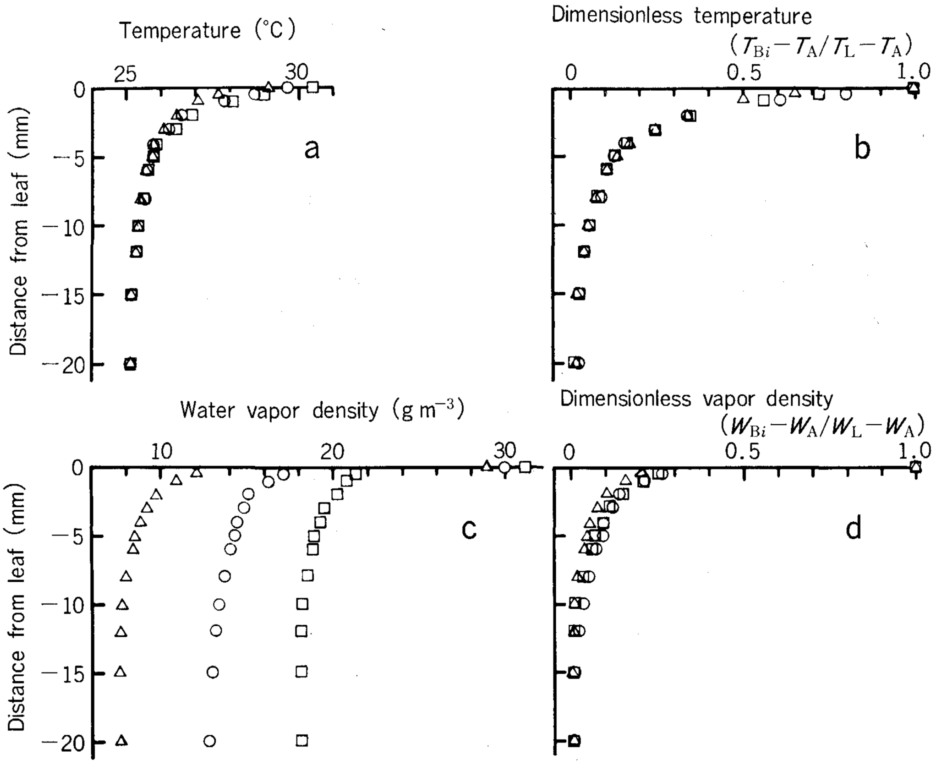

Fig. 3. Profiles of temperature (a), dimensionless temperature (b), water vapor density (c) and dimensionless vapor density (d) of air near the abaxial surface of a cucumber leaf under the tungsten light at respective saturation deficits of 5 (□), 10 (○) and 15 g m^{-3} (△) at constant temperature of 25°C and lateral wind velocity of 0.7 m s^{-1} of ambient air outside the boundary layer (W_{Bi}, W_A, W_L, T_{Bi}, T_A and T_L are explained in Fig. 1).

humidity profile within the boundary layer of the transpiring leaf strictly depended on the transpiration regulated by stomatal and cuticular resistance.

Figure 2 shows the profiles of temperature and humidity boundary layers on abaxial leaf surface under the light at respective air temperatures (T_A) of 20, 25 and 30°C at constant SVD of 10 g m^{-3} and V of 0.7 m s^{-1}. T_L-T_A was smaller at the higher T_A and the leaf was exposed to larger temperature gradient near the leaf surface at the lower T_A: T_L-T_A at the higher T_A of 30°C remained at about 3°C, but T_L-T_A at the lower T_A of 20°C reached to about 8°C. Respective profiles of $T_{Bi}-T_A/T_L-T_A$ appeared in the same patterns without influences of T_A and T_L-T_A relating to buoyancy. The profile of humidity boundary layer at each T_A was different from each other. $W_{BO}-W_A$ was larger at the higher T_A, and this larger $W_{BO}-W_A$ was considered to be attributed to the higher transpiration rate caused by stomata responding to the higher T_A. In the previous paper (*4*), it has been reported that leaf conductances and transpiration rates in cucumber plants are influenced by T_A in a range of 20 to 35°C and become higher at higher T_A. In this experiment, *EVDD* was found to be larger at the lower T_A of 20°C because of the lower transpiration rate: *EVDD* at T_A of 20°C was about 18 g m^{-3} which reached to 90% of

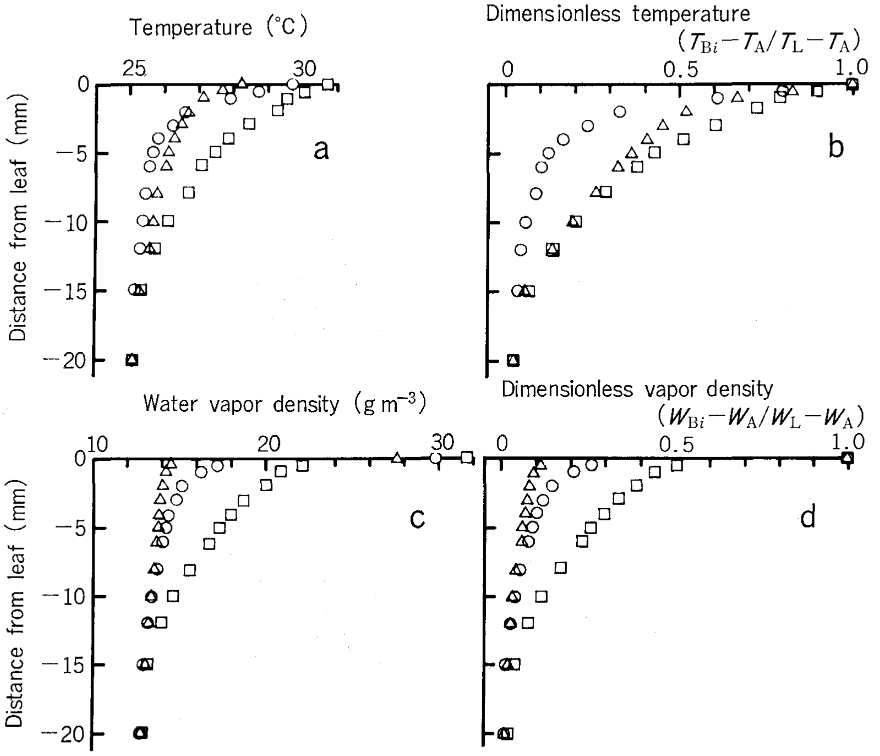

Fig. 4. Profiles of temperature (a), dimensionless temperature (b), water vapor density (c) and dimensionless vapor density (d) of air near the abaxial surface of a cucumber leaf under the tungsten light at respective lateral wind velocities of 0.35 (□), 0.70 (○) and 1.4 m s^{-1} (△) at constant temperature of 25°C and saturation deficit of 10 g m^{-3} of ambient air outside the boundary layer (W_{Bi}, W_A, W_L, T_{Bi}, T_A and T_L are explained in Fig. 1).

W_L-W_A, and *EVDD* at the higher T_A of 30°C remained at 9.5 g m^{-3} which was 60% of W_L-W_A. Although *SVD* of ambient air was kept constant at 10 g m^{-3}, *EVDD* at leaf surface decreased with higher T_A, and *EVDD* became larger at the lower T_A. Thus, profile of humidity boundary layer was affected by stomatal response to T_A. So that, stomatal complexes in leaf epidermis was exposed to different vapor density gradients even under a constant *SVD* of ambient air.

Figure 3 shows profiles of temperature and humidity boundary layer on abaxial leaf surface under the light at respective vapor density differences (*SVD*) of 5, 10 and 15 g m^{-3} at constant T_A of 25°C and V of 0.7 m s^{-1}. Profiles of T_{Bi} and $T_{Bi}-T_A/T_L-T_A$ at each *SVD* were almost the same: T_L was a little higher at the higher *SVD*, but this difference in T_L was only about 1°C. In the profile of humidity boundary layer, W_{Bi} was lower and W_L-W_{BO} (*EVDD*) and W_L-W_A were larger at the higher *SVD* because of the lower W_A; for example, *EVDD*and W_L-W_A at the higher *SVD* of 15 g m^{-3} were about 1.6-fold larger than those at the lower *SVD* of 5 g m^{-3}. On the other hand, difference in $W_{BO}-W_A$ was remarkably small among the profiles at each *SVD*: The difference was within 1 g m^{-3}. This suggests that transpiration rates at each *SVD* are nearly equal to each other. Profile of $W_{Bi}-$

W_A/W_L-W_A was also almost the same: Percentage of *EVDD* to W_L-W_A was about 80% at the higher *SVD* of 15 g m^{-3} and 75% at *SVD* of 10 and 5 g m^{-3}. In the previous paper (*4*), it has been reported that leaf conductances in cucumber plants become lower at higher *SVD*, and transpiration rates are kept at almost same level without influence of *SVD* in a range of 5 to 20 g m^{-3}. From these facts, it could be conceivable that the equality of $W_{BO}-W_A$ can be brought by stomatal response to humidity (lower leaf conductance at higher *SVD*). Thus, the profile of humidity boundary layer on transpiring leaf was affected directly by *SVD*, and this *SVD* effect was influenced by the stomatal response to humidity and was different from the *SVD* effect predicted in the evaporating surface such as the surface of the wetted filter paper.

Figure 4 shows profiles of temperature and humidity boundary layer on abaxial leaf surface at respective wind velocities (V) of 0.35, 0.7 and 1.4 m s^{-1} at constant T_A of 25°C and *SVD* of 10 g m^{-3}, where the respective V of 0.35, 0.7 and 1.4 m s^{-1} were equivalent to Reynolds numbers of 0.45×10^4, 0.90×10^4 and 1.8×10^4. T_L was lower at the higher V, and there were clear differences in T_{Bi} and $T_{Bi}-T_A/T_L-T_A$ among the profiles at each V: At V of 0.35 and 1.4 m s^{-1}, temperature gradient near the leaf surface was smaller, and the temperature boundary layer was thicker than those at V of 0.7 m s^{-1}. These differences were estimated to be caused by the effect of V on characteristics of air current within the boundary layer. From the facts that Reynolds number at V of 1.4 m s^{-1} was twice as large as that at V of 0.7 m s^{-1} and the leaf was a little flapping, the boundary layer was considered to be more turbulent at V of 1.4 m s^{-1}. At V of 0.35 m s^{-1}, free convection by buoyancy was supposed to be more active than that at V of 0.7 m s^{-1}, where Grashof number/(Reynolds number)^2 indicating the relative dominancy of free convection to forced convection (*6*) was 5-fold larger at V of 0.35 m s^{-1}, as compared with that at V of 0.7 m s^{-1}. In the humidity profile, the effect of V appeared in sweeping away the moistened air near the leaf surface. $W_{BO}-W_A$ at the higher V of 1.4 m s^{-1} were remarkably lower than that at the lower V of 0.35 m s^{-1}: $W_{BO}-W_A$ remained at only 1.5 g m^{-3} at V of 1.4 m s^{-1}, but it reached to 9.5 g m^{-3} at V of 0.35 m s^{-1}, and *EVDD* at V of 1.4 m s^{-1} reached to 90% of W_L-W_A, where *EVDD* at the lower V of 0.35 m s^{-1} was kept at 50% of W_L-W_A. The lower $W_{BO}-W_A$ were considered to be attributed to the lower boundary layer resistance at the higher V and attributed to the lower transpiration rate caused by stomatal closure responding to the higher V (*3*): The larger *EVDD* at the higher V can be supposed to make the stomatal response to humidity more sensitive at the higher V and supposed to bring stomatal closure, as reported by Bunce (*1*). Thus, it could be revealed that the profile of humidity boundary layer is affected by V outside the boundary layer through the effect of V on boundary layer resistance and stomatal response.

In this experiment, the effects of air current and stomatal response on the humidity profile within the leaf boundary layer were elucidated, and it could be conceivable that stomatal responses closely relate to the profile of humidity to which stomatal complexes are exposed directly.

REFERENCES

1. Bunce J. A. (1985) Effect of boundary layer conductance on the response of stomata to humidity. *Plant, Cell and Envir.* **8**, 65–57.
2. Grace J., Malcolm D. C. and Bradbury I. K. (1975) The effect of wind and humidity on leaf diffusive resistance in Sitka spruce seedlings. *J. App. Ecol.* **12**, 931–940.
3. Grace J. and Wilson J. (1976) The boundary layer over a *Populus* leaf. *J. Exp. Bot.* **27**, 231–241.
4. Kitano M., Eguchi H. and Matsui T. (1983) Analysis of heat balance of leaf with reference to stomatal responses to environmental factors. *Biotronics* **12**, 19–27.
5. Kitano M. and Eguchi H. (1987) Air humidity within boundary layer of a transpiring leaf. I. Relationship between transpiration and water vapor density at leaf surface. *Biotronics* **16**, 39–45.
6. Monteith J. L. (1973) Heat transfer. (i) Convection. Pages 100–118 *in Principles of Environmental Physics*. Edward Arnold Ltd., London.
7. Schlichting H. (1979) *Boundary-Layer Theory*. McGraw-Hill Book Company, New York.
8. Yabuki K. and Nishioka M. (1973) Studies on the effect of wind speed on photosynthesis. (3) The structure of air flow near leaf surface. *J. Agr. Met.* **29**, 173–177 (in Japanese with English summary).