Leaf Temperature in Relation to Meteorological Factors.
(2) Leaf Temperature Variation with Air Temperature and Humidity

Tetsuya HASEBA and Daijiro ITO

Division of Agricultural Meteorology, College of Agriculture, Ehime University, Matsuyama 790, Japan

Abstract

The plant-leaf temperature is calculated as air temperature and/or relative humidity varies after solving the stationary heat budget equation of a single leaf. Stomatal aperture changes are assumed to be dependent on short-wave radiation and air temperature when the air temperature varies, and on relative humidity in addition to the former two factors when relative humidity varies. Because the convection coefficients for heat and water vapor transfer through the boundary layer on a leaf are corrected by buoyancy, the leaf temperature is more accurately estimated at low wind speeds. Moreover, the coefficients include the effects of temperature distribution over the leaf surface, turbulence of the air flow within a plant canopy and leaf fluttering.

There is a certain point at which leaf and air temperatures are equal. Below that point, the leaf temperature is always higher than the air temperature, while above that point the reverse is true even though both temperatures continue to rise. This so called equality temperature depends on meteorological factors. In addition, it is suggested that the equality temperature depends, in part, on the plant species.

Leaf temperature increases with increasing relative humidity when the stomatal aperture remains fixed. When the aperture depends on the relative humidity, the leaf temperature variation is affected by the stomatal behavior.

1. Introduction

The leaf temperature of a plant is closely related to the meteorological conditions and the physical properties and physiological processes of the plant. Temperature is an important factor concerning the growth of the plant. The dependence of the leaf temperature on wind speed and solar radiation has been investigated (Haseba and Ito, 1980). The relationships between leaf temperature and air temperature or relative humidity are examined here after solving the heat budget equation of the leaf.

Gates and Papian (1971) obtained much information on leaf temperature and transpiration related to meteorological factors and stomatal aperture through a computer simulation. These results, however, were based on the assumption

that the stomatal aperture regulating water loss by transpiration was independent of meteorological factors. In this paper, the internal transfer coefficient for water vapor in terms of stomatal aperture is given as a function of meteorological factors i.e., solar radiation, air temperature and relative humidity. Because the effect of buoyancy (Haseba, 1973b) is taken into account when calculating the leaf boundary-layer transfer-coefficients for heat and vapor, the leaf temperature can be more accurately estimated even at low wind speeds. The forced convection transfer coefficient is thus affected by the leaf temperature distribution on the surface (Takechi, 1973; Takechi and Haseba, 1973), the turbulence of the air flow within a canopy (Haseba, 1973a) and leaf fluttering (Haseba, 1975b). Moreover, the heat budget equation includes the non-linear terms of the leaf temperature, which are those of long-wave radiation emitted from the leaf surface and latent heat by transpira-
tion. The relationships between the leaf temperature and the meteorological factors are graphically represented using an analog computer. The relationships observed for the leaves of eggplants and oats are compared with the simulation results.

2. Methods

2.1 Simulation

Leaf temperature or the difference between leaf and air temperatures was estimated by solving the heat budget equation of a leaf (Haseba and Ito, 1980) in relation to air temperature and/or relative humidity. It was assumed that the stomata on both surfaces of a leaf were equivalent in number and size and that the leaf had sufficient moisture available for transpiration in its interior where the air was saturated with water vapor at the leaf temperature. The equation is given by

$$\mu R_s + \beta L (R_{i,sky} + R_{i,sur}) - \beta L R_{i,L} = H + L w$$

where, $R_s$ is the incident short-wave radiation on the leaf surface (ly·sec$^{-1}$); $R_{i,sky}$ and $R_{i,sur}$ are the incident long-wave radiations on the surface from the sky and the surrounding area, respectively; $R_{i,L}$ is the black-body long-wave radiation at the leaf surface; $H$ is the sensible heat flux-density at the surface (ly·sec$^{-1}$); $L$ is the latent heat of vaporization (cal·g$^{-1}$); $w$ is the vapor flux-density (g·cm$^{-2}$·sec$^{-1}$); $\mu$ and $\beta L$ are leaf absorptivities of short- and long-wave radiations, respectively. Details are given in the papers by Haseba (1975a) and Haseba and Ito (1980).

In solving the equation, a local point 2 cm distant in the air flow direction from the leading edge of the leaf was used. This local leaf temperature agrees with the mean temperature of a 6 cm elliptic leaf in the flow direction (Haseba and Takechi, 1972).

In calculating the relationship between leaf and air temperatures, an internal transfer coefficient for water vapor was assumed to be dependent on short-wave radiation and air temperature (Haseba, 1973c). In Fig. 1-A the dependence of the internal transfer coefficient on short-wave radiation is shown. This correlation was derived from the relationships between stomatal aperture and short-wave radiation observed in the experiments of Dale (1961), Kuiper (1961), Haseba and Ito (1971) and Haseba (1973c). The stomatal aperture widens with radiation. In Fig. 1-B the dependence of the internal transfer coefficient on air temperature in relative value, which was derived from the information about the stomatal aperture (Wilson, 1948; Stalfelt, 1962), is shown. The stomatal aperture widens with the air temperature. In this calculation, an internal transfer coefficient was given for a fixed short-wave radiation from Fig. 1-A. This was a coefficient at an air temperature of 40°C, and the coefficient changed when the air temperature went below 40°C, according to the pattern representing the relation between the internal transfer coefficient and the air temperature.

Relationships between leaf temperature and relative humidity were obtained in three cases after an internal transfer coefficient was given for the set of a certain short-wave radiation and a specific air temperature. In the first, the stomatal aperture was constant as relative humidity varied. In the second, stomata opened hydropassively at low humidities. A coefficient derived in the same way as in the first case was the maximal one at the lowest humidity. The stomatal aperture, from which the coefficient was derived, changed in the pattern given by Tagawa (1936). Fig. 2 shows the pattern of change in the internal transfer coefficient.
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Fig. 2. Relative humidity (R.H.) dependence of internal transfer coefficient ($D_L$) when stomata open hydropassively.

Fig. 3. Same as Fig. 2, when stomata close hydroactively.

2.2 Experiment
Mature plants of eggplants and oats were used for the experiments to discover the relationships between leaf and air temperatures. They were planted in pots of 1/2,000 or 1/5,000 a, and grown in a plastic enclosure. A vigorous plant was chosen and translocated into a room. A single leaf was horizontally held in a leaf chamber which was used to examine photosynthesis, and irradiated with incandescent lamps through a water bath filter. A constant air temperature was maintained within the chamber by adjusting the temperature of water in the bath around the bottom of the chamber. Stationary leaf temperature was measured at the center of the abaxial surface with a copper-constantan thermocouple 0.1 mm diameter. Air temperature was measured with a similar thermocouple. The intensity of short-wave radiation was measured by a thermopile pyranometer and a spectroradiometer. The flow speed in the center of the chamber was about 0.7 m·sec$^{-1}$.

3. Results and discussion

3.1 Leaf temperature variation with air temperature
Fig. 4 shows the relationships between leaf-air temperature difference and air temperature ranging from 0°C to 40°C at a fixed wind speed of 0.2 m·sec$^{-1}$ for various short-wave radiations of 0.3 to 1.2 ly·min$^{-1}$ and relative humidities of 0 to 100%. The maximal internal transfer coefficient

Fig. 4. Leaf-air temperature difference ($\Delta \theta_L$) vs. air temperature ($\theta_A$), at a wind speed of 0.2 m·sec$^{-1}$.
at an air temperature of 40°C is represented beside each curve in the figure. The temperature difference decreases with increasing air temperature. The patterns are almost linear.

Although the illustration is not presented, similar relations were obtained for a high wind speed. These results agree closely with those of Gates and Papian (1971). The rate of declining temperature difference with increasing air temperature is high under the condition of intense sunlight, dry air and light wind.

In intense sunlight, the temperature difference is generally positive at air temperatures lower than a point above which there is a tendency for the temperature difference to be negative.

Fig. 5 shows the relationships between leaf and air temperatures for short-wave radiations of 1.2 and 0.3 ly·min⁻¹ at a wind speed of 0.2 m·sec⁻¹. These were prepared to examine the effect of humidity on the relationship. Leaf temperature is equal to air temperature at a crossover point below which the leaf is warmer than the air and above which the reverse is true. This crossover point has been called “equality temperature” by Linacre (1964 and 1967). The existence of such a temperature was also found by Gates (1964) and Drake et al. (1970). Under a constant relative humidity the equality temperature is higher than under that of constant vapor pressure when the air is warm and moist.

In Fig. 6 the equality temperature as a function of short-wave radiation for various relative humidities from 0 to 80% under fixed wind speeds of 0.2 and 1.0 m·sec⁻¹ is shown. In air near 100% relative humidity, the equality temperature was so high, due to reduced transpiration (Haseba, 1975a), that the curves were rejected. As short-wave radiation and relative humidity become higher and wind speed lowers, the equality temperature becomes high. The major reason why the equality temperature exists is due to long-wave radiation emitted from the leaf surfaces increasing proportionally to the 4th power of the absolute temperature of the leaf. At high air temperatures, the energy loss due to the emission of long-wave radiation is relatively large compared to that due to the other terms in the heat budget of the leaf. Therefore, it is necessary to lower the leaf temperature below the air temperature in order to balance energy losses and gains. After a simplification of the long-wave radiation terms, the heat budget equation of a leaf with equivalent stomata on both surfaces can be written (Haseba, 1973b) as

\[ \mu R_B + \beta_L \sigma (\beta_A \Theta_A + (\beta_A - 2) \Theta_L) \]

\[ = 2 h_B d \Theta_L + 2 L D_{TR} (C_0 + r A \Theta_L), \]

where, \( \Theta_A \) and \( \Theta_L \) are air and leaf temperatures (K); \( D_{TR} \) is the vapor transfer coefficient for transpiration (cm·sec⁻¹); \( C_0 \) is the saturation deficit of air (g·cm⁻³); \( h_B \) is the boundary-layer
heat transfer coefficient (cal·cm⁻²·sec⁻¹·°C⁻¹); \( \beta_A \) is the numerical coefficient; \( \sigma \) is Stefan-Boltzmann's constant; and \( \tau \) is the temperature gradient of saturation vapor density (g·cm⁻³·°C⁻¹). An air temperature at which the leaf-air temperature difference is zero is the equality temperature (\( \Theta_e \)),

\[
\Theta_e^* = \left( \mu R_s - LD_{TR} C_0 \right) / \beta_L \left( 2 - \beta_L - \beta_A \right) \sigma.
\]

For a leaf without transpiration due to stomatal closing, the equality temperature is only about 87°C, at a short-wave radiation of 0.6 ly·min⁻¹. For a leaf with transpiration the equality temperature is lower.

Linacre (1964 and 1967) presented the relationship between leaf and air temperatures using many observations in previously published papers and estimated an equality temperature of 33°C. Drake et al. (1970) found that the crossover occurred near 35°C for three wind speeds and two humidity levels. There are several observations about the dependence of leaf temperature on air temperature (Gates et al., 1968; Horie, 1980). These results agree, in tendency, with the simulation presented here.

Fig. 7 shows experimental relationships between leaf and air temperatures observed for the leaves of eggplants and oats under a stationary income of short-wave radiation and a constant air flow speed. For eggplants the equality temperature covered a temperature range of 31° to 34°C and did not vary greatly between two levels of radiation. For oats, the equality temperatures were about 19° and 17°C for short-wave radiations of 0.52 and 0.32 ly·min⁻¹, respectively. The influence of meteorological factors on the measured equality temperature seems to be less than predicted.

Linacre (1967) mentioned a number of plants with a similar equality temperature. Because Linacre collected the results for leaves in sunlight and with good water supply, the equality temperatures might tend to be one point. Drake et al. (1970) stated that the common crossover point of leaf temperature occurred near 35°C. Because the wind speed at which the experiments were made was relatively high, the dependence of the equality temperature on wind speed is weak. When wind speed is lower than 1 m·sec⁻¹, the dependence is strong as presented in this simulation. Although some discrepancies exist between the measured and the predicted, the results obtained from both eggplants and oats show that there is a remarkable difference in equality temperature between these two plant species. This suggests that crops originating in a low air temperature climate, such as oats, have low equality temperatures and that crops growing at high temperatures, such as eggplant, have high equality temperatures. The equality temperature seems to be an important property of a plant species.

A previous research shows that the optimum temperature for photosynthesis is near the equality temperature (Ito et al., 1981). In addition, Sawada (1970) pointed out the dependence of the optimum temperature on the temperature condition during the growing period. These facts and the
review by Björkman (1981) indicate that the leaf temperature is raised by the physiological activity of a plant, such as transpiration (Drake et al., 1970) and the diffusion resistance within the leaves (Gates, 1964), to a higher temperature when the air is cool, and a lower temperature when the air is warm. Such an adjusted temperature is an equality temperature. The relationships between the optimum temperature and equality temperature requires further investigation.

3.2 Leaf temperature variation with relative humidity

(i) When stomatal aperture is constant.

Because the relation between stomatal aperture and relative humidity is complicated (Ketellapper, 1959; Raschke, 1970), the dependence of leaf temperature on humidity was calculated, first, when the stomatal aperture remained constant as the relative humidity varied. However, it was dependent on short-wave radiation and air temperature.

Fig. 8 shows the examples of the relationship between the leaf-air temperature difference and the relative humidity ranging from 0 to 100% for short-wave radiations of 0.3 to 1.2 ly·min⁻¹ under fixed conditions of air temperatures from 0⁰ to 40⁰C and a wind speed of 0.2 m·sec⁻¹. As relative humidity increases, leaf temperature increases in linear proportion. This results from suppressed transpiration in moist air. The rate of the increment of the leaf temperature is high in warm weather. In cool weather, the change in leaf temperature is slight due to little changes in transpiration. At air temperatures of 40⁰, 30⁰ and 20⁰C, the curve of the leaf-air temperature difference vs. humidity for a low short-wave radiation of 0.3 ly·min⁻¹ crosses with those for other radiations. This results from the dependence of the stomatal aperture on the air temperature and short-wave radiation. Because the stomatal aperture is given to be relatively small under the conditions of a high air temperature and a low short-wave radiation, transpiration is relatively suppressed so that the leaf temperature is raised. At a high wind speed, similar relationships were observed.

(ii) When stomata open as humidity decreases.

Fig. 9 shows the relationships between leaf-air temperature difference and relative humidity. These resulting patterns are similar to the results obtained by the constant stomatal aperture simulation. Although the leaf temperature increases with relative humidity, in moist air leaf temperature is remarkably raised because of suppressed transpiration by a relatively small internal transfer coefficient. Therefore the curves are concave.

(iii) When stomata close as humidity decreases.

At a high humidity, the leaf-air temperature difference is nearly equal to that for the constant stomatal aperture simulation (Fig. 10). In relatively warm air, leaf temperature elevates remarkably at a low humidity due to suppressed transpiration by stomatal closing. Therefore the curves of the relationship are concave. The crossing of curves for various short-wave radiations in the figure originates from the humidity dependence of the internal transfer coefficient. Such crossing of curves diminishes at low air temperatures when the internal transfer coefficient changes smoothly with relative humidity.

Observations of the dependence of leaf temperature on humidity are rare because of the
4. Conclusion

When the stomatal opening grows in the pattern of a saturating curve with increasing short-wave radiation and air temperature, leaf temperature is relatively high under a low air temperature range. As humidity remains constant, the leaf-air temperature difference decreases almost linearly with increasing temperature until an air temperature is reached above which the leaf becomes cooler than the air. The equality temperature, where the leaf-air temperature difference changes from positive to negative, is high when short-wave radiation and relative humidity are high and wind speed is low.

It is indicated that the equality temperature is partly dependent on the plant species and belongs to an inheriting factor resulting from the ground from which it originates. Moreover, it is suggested that the equality temperature is related to the optimum temperature for photosynthesis.

Variations in leaf temperature related to relative humidity are complicated. When the changes in stomatal aperture result from short-wave radiation and air temperature in a usual manner and are independent of the humidity, leaf temperature increases linearly as the air becomes moist. Although leaf temperature rises with the relative humidity when stomata open hydropassively at low humidities, it rises more markedly at high humidities due to the closing of the stomata. When stomata close hydroactively at low humidities, leaf temperature is relatively high.

References

5) Gates, D. M., Alderfer, R. and Taylor, E.,


植物の葉温と気象要素との関係
(2) 気温・湿度の変化に伴う葉温の変化

長谷場徹也・伊藤代次郎
（愛媛大学農学部農業気象学研究室，松山市樽味 3-5-7）

要約

葉の熱収支式を解いて，葉温と気温もしくは相対湿度との関係を求めた。この際，熱及び水蒸気の葉面境界層輸送係数には，浮力，葉面温度分布，群落内の気流の乱れ及び葉の揺れの効果を考慮した。また，気孔開度は，日射量，気温及び相対湿度の関数として与えた。

気孔開度が日射量によるとともに気温の上昇に伴って飽和曲線的に大きくなる場合に，気温が低いと葉温は比較的高いが，湿度が一定で気温が上昇すると，葉気温差はほぼ直線的に小さくなって，ある気温で葉温は気温と等しくなり，それ以上の気温で葉温は気温より低くなる。この“equality temperature”は日射が強く相対湿度が高くまた風が弱いほど高くなる。さらに，equality temperature は作物の生まれた土地の温度条件に関連する遺伝的特性としてきたこと，ならびに，equality temperature は光合成の適温に重要な意味を持つことが示唆された。

気孔開度は日射量と気温とに依存するが，相対湿度に対しても一定の場合，高湿になるに従い，葉温は直線的に上昇する。次に，気孔が低湿時に開く場合，葉温は湿度の上昇に伴ってほぼ直線的に上昇するが，高湿時に気孔が相対的に閉じて葉温はやや高くなる。低湿時には，気孔が閉じる場合には，葉温は相対的に高くなる。

実測値から得られた葉温と各気象要素とのそれぞれの関係は葉の熱収支のシミュレーションの結果とはほぼ一致した。