Mass Transfer across the Boundary Layer on Plant Leaves.
(1) Preliminary Study of Water-Vapor Transfer from a Leaf-like Flat Plate with Separated Evaporation Sources.

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Abstract

In order to clarify the mass transfer through the boundary layer on a plant leaf, preliminary studies were made concerning the forced-convection transfer of water vapor from the wet strips arrayed across the wind on a rectangular plate in parallel with air flow.

The effect of the vapor-concentration boundary-layer developed at the upstream strips on the transfer from the downstream strip was examined for different spacings between strips. The transfer coefficient for a flat plate with separated wet strips was derived on the analogy of the coefficient for heat transfer from a plate having unheated starting section.

Further, the transfer coefficient for a plant leaf with stomates was estimated by adding the edge effect of a small object on the transfer to the analyzed results concerning the transfer from a plate with multi-evaporation-sources. It is suggested that the transfer coefficient for a plant leaf with normally opening stomates is to be fairly larger than the one for a leaf-shaped plate with whole surface wetted and without edge effect.

1. Introduction

In the studies of transpiration or photosynthesis in plant leaves, the coefficient of (or resistance to) mass transfer across the boundary-layer on a leaf-shaped plate with homogeneous surface has been used, although water-vapor or CO$_2$-gas are actually transferred through mainly the scattered stomates in the epidermis of leaves. Since the stomates are separated sources or sinks for gases, the coefficient of mass transfer across the boundary-layer on a real leaf is considered to be different from that for a leaf-shaped plate.

Molecular diffusion of gas through a multi-perforate septum which is to simulate a stomatal system has been studied in several literatures (e.g., Ting and Loomis, 1964). However, there is little knowledge about convection mass transfer through the boundary-layer over a plate with separated sources or sinks of very small size at the surface.

Recently, it has been reported that mass transfer co-efficient measured for real leaves is larger than the estimate from the theory of boundary-layer transfer on an isothermal flat plate. Such an enhancement of transfer may be partly due to the factors such as buoyancy, variation of mass concentration over the leaf surface, curvature and roughness of leaf surface, tilting and fluttering of leaves, and turbulence of air-flow within canopies. It may also be due to the factors which have not yet been pinpointed.

In the present paper, the fundamental characteristics of water-vapor transfer from a flat rectangular plate with separated evaporation sources on it are discussed based on the several experimental results. Furthermore, the value of vapor transfer coefficient applicable to a plant leaf is suggested after this study.

2. Literature survey on the water-vapor transfer coefficient for a plant leaf and on the factors affecting the boundary-layer transfer

The convection vapor transfer coefficient for leaves in the fields has been estimated by many workers. In several literatures, the significantly larger transfer co-
efficient compared with that predicted by the boundary-layer theory used hitherto has been reported.

HUNT et al. (1968) pointed out that, if the value of stomatal resistance measured with a diffusion porometer within a sunflower canopy was used in a heat balance equation for a leaf, the evaluated boundary-layer resistance was significantly smaller than the estimate from boundary-layer formulae. In terms of the average boundary-layer transfer coefficient, the measured value was 5 to 14 times greater than the calculated value for an isothermal circular plate.

PEARMAN et al. (1972) showed, in correction of the data taken by KANEMASU et al. (1969), that the boundary-layer transfer resistance of leaves within a snap bean canopy is substantially less than that expected from simple boundary-layer transfer formulae for given wind flow and leaf size. With the use of the values obtained by PEARMAN et al., the ratio of the actual transfer coefficient to that for an isothermal circular plate in parallel with air flow becomes approximately between 1 and 3.

As for the vapor transfer coefficient for a leaf-shaped plate with wet surface, MONTEITH (1965) reviewed the experimental results by several workers and proposed, on the basis of RASCHKE’S data (1956), a formula of the vapor transfer coefficient for a plant leaf in the field. This value of the coefficient exceeds the theoretical one by a factor of about 1.7.

The transfer coefficient for leaves derived from the turbulent diffusion coefficients within a corn canopy was much larger than the value expected from the boundary-layer theory (BROWN and COVEY, 1966).

On the other hand, PEARMAN et al. (1972) found that the heat transfer coefficient for horizontal isothermal circular discs placed above a corn canopy was about twice of the value of a simplified leaf-model. TAKECHI and HASEBA (1962) and SLATYER and BIERHUIZEN (1964) also pointed out that the measured heat-transfer coefficient for a leaf was larger than the value obtained from the laminar boundary-layer theory.

There are several factors which affect the boundary-layer transfer from leaves in the field.

1) Correction due to Lewis relation

Theoretical value of the coefficient of mass transfer across the boundary layer is commonly given by analogy of heat transfer. According to the boundary-layer theory, the following two formulae are written:

\[ Sh = Le^{1/3} A \cdot Sc^{1/3} Re^{1/2} \]

\[ D = Le^{2/3} A \cdot Sc^{1/3} Re^{1/2} d/l \]

where \( Sh \) is Sherwood number, \( D \) = mass transfer coefficient, \( Le = Sc/Pr \) is Lewis number, \( Sc = Schmidt number \), \( Pr = Prandtl number \), \( Re = Reynolds number \), \( d = \) molecular diffusion coefficient of gas, \( l = \) characteristic length of a plate and \( A = \) a numerical coefficient which appears in Nusselt number definition (\( Nu = A \cdot Pr^{1/3} Re^{1/2} \)).

The value of \( Le \) for water-vapor transfer in air is about 0.87 under normal condition of temperature, humidity and pressure; accordingly \( Le^{1/3} \approx 1.05 \) and \( Le^{2/3} \approx 0.90 \). Therefore, in order to obtain vapor transfer coefficient from the formula applicable to heat transfer coefficient, the numerical factor \( A \) must be reduced by a factor of about 0.9. However, it is not a serious factor affecting the mass transfer and in most cases this correction has not been made. Therefore, this correction is not taken into account in the present paper.

2) Buoyancy effect

The effect of buoyancy in the transfer process has been analyzed by MORT (1961) and SPARROW and MINKOWICZ (1962). For instance, the partition of free convection in the total transfer rate over a rectangular plate in longitudinal air flows with speeds of 0.5 and 1 m/s is about 20% and 10% of the total, under a given meteorological condition, respectively (HASEBA, 1973c; HASEBA and TAKECHI, 1973). In the case of the lower Reynolds number and larger difference of density of air between the immediate vicinity of the surface and outside the boundary layer, the buoyancy effect is larger.

Unless the buoyancy effect is excluded from the convection transfer process, the exponent of wind speed which is involved in the formula of the forced-convective transfer coefficient will be apparently smaller than 0.5 even in the case of laminar boundary layer. The decrease in the exponent is larger for lower wind speed.

In other words, if the transfer coefficient is related to the 0.5-th power of wind speed, the numerical factor has to be larger than that adopted in the boundary-layer theory. THOM (1968) also mentioned that correction for buoyancy effect was needed for RASCHKE’S evalua-
tion of convective transfer coefficient from experiments.

3) Effect of the variation of mass concentration over the surface

It is well known that non-homogeneity of the surface temperature or mass concentration over the surface influences the transfer on plates (Levy, 1972 etc.). There is a report in which the effect of the temperature variation on the heat transfer from a leaf model was not noticed (Parkhurst et al., 1968a, b). However, as Cowan (1972) and Takechi (1973) pointed out, it should be noted that the forced-convection heat transfer coefficient for an isothermal plate can be used for that for a non-isothermal plate if the surface temperature of the plate is properly chosen. Furthermore, Takechi and Haseba (1973) have clarified the relationship between the vapor transfer coefficient and the variation of surface vapor-concentration over a leaf-shaped plate.

4) Curvature of a leaf

Convective transfer coefficient for curved leaves must be different from the one for flat plates (Thom, 1968 and Schuepp, 1972). Schuepp observed that the convective transfer rate for a cupped leaf model exceeded that for a rigid plate by a factor of about 2.

On the contrary, Parlange (1970) and Parlange et al. (1971) suggested the relatively little effect of surface curvature on the transfer. Therefore, the effect of the curvature on the transfer has not yet been satisfactorily clarified by experiments. The effect of moderate curvature may be discussed by investigating the effect of the inclination of a leaf to the air flow.

5) Surface roughness of leaves

The surface of plant leaves with veins and hairs is not dynamically smooth. As it is well known, turbulence promoters at the surface of a plate enhance the convective transfer (Knudsen and Katz, 1958). Wolpert (1962) recognized some enhancement of the transfer rate due to leaf hair. While, Yabuki et al. (1970) reported that the thickness of the boundary layer over a leaf with hair exceeded that over a smooth plane, if so, the leaf hair reduces the transfer coefficient.

On the other hand, Hunt et al. (1968) argued that the presence of veins and hairs affects only the transition of the boundary-layer flow from laminar to turbulent. It should be noted that the occurrence of transition in the lower range of wind speed reduces the convective transfer coefficient in turbulent boundary layer as compared with that in the laminar range (Takechi and Haseba, 1967).

As mentioned above, there have not been satisfactory experimental results about the effects of the surface roughness and of an increase in surface area due to the roughness on the transfer rate. It seems, however, that veins and hairs of normal plant leaves have not a large effect on the convective transfer coefficient.

6) Orientation of leaves for the air flow

Most leaves within plant canopies are located in various orientation for wind. Thom (1968) found that the transfer coefficient for a leaf-model which is tilted to the direction of air flow in a wind tunnel differs about 10% from that for a flat plate in parallel with air flow. Parkhurst et al. (1968a, b) examined the dependency of the average heat transfer coefficient for tilted elliptic metal plate on the attack angles. But the obtained result is somewhat complicated. Schuepp (1972) reported that a change in orientation of the leaf cluster to the air flow produced less than 10% change in average transfer coefficient.

In the above papers, the effect of the tilting of a plate on the transfer coefficient has not been systematically studied. Haseba (1973a) studied the water vapor transfer from the wet surface of a plate inclined to the air flow in a tunnel, and argued that the effect of the inclination on the forced-convection transfer resulted mainly from the formation of pressure gradient at the surface. Then, it was shown that the average coefficient of vapor transfer from both sides of a plate, except for the attack angles between 10° to 30°, might be approximated by the one evaluated for a plate in longitudinal flow. Further, it was suggested that the transfer coefficient for a tilted plate with the attack angles from about 10° to 30° might not be represented by the 0.5-th power law of wind speed owing to the separation of the boundary layer at the leeside surface. The leaf inclination which influences the transfer is expected to affect the transfer in the presence of turbulence of the air flow within canopies, and may be a basic factor to be considered in leaf fluttering.

7) Turbulence of air flow

While Thomas (1965), Morohashi (1966) and Jukhan and Seroy (1967) reported the experimental results that the turbulence increased the transfer coefficient, Schlichting (1960), Kestin et al. (1961),
BUYÜKTÜR et al. (1964) and KESTIN (1966) have stated that the effect of the turbulence of air flow on the transfer is little and that a large effect associated with the free-stream turbulence can be produced only in the presence of pressure gradient over the surface of a given object. It is noted here that the Blasius-type gradient of stream velocity across the boundary layer has been found in a weak turbulent flow by SCHLICHTING (1960) and YABUKI and NISHIOKA (1973). From these studies, it may be concluded that an increase in the forced-convection transfer coefficient by free-stream turbulence is produced if pressure gradient over the surface is accompanied.

In the experiments by PARKHURST et al. (1968a, b) on heat transfer from leaf-models which were set in the foliage and set behind a foliage, the heat transfer coefficient was obtained to be larger by a factor of about 1.2 than the theoretical one for a flat plate with uniform surface temperature in longitudinal flow. PARLANGE et al. (1971) showed that the increase in transfer coefficient for a tobacco leaf in the air flow with turbulence of some favorable scale was as high as by a factor of about 2.6. It is questionable whether the effect of turbulence could be isolated in the above works.

On the contrary, HASEBA and TAKECHI (1973) found that the water-vapor transfer coefficient for a horizontal flat plate placed above the bare ground in the field was hardly affected by the turbulence of air flow. Furthermore, HASEBA (1973b) showed that the transfer coefficient on a horizontal plate within a plant canopy where the turbulent air flow was not parallel to the leaf surface was higher by a factor up to about 1.3 than the theoretical one in the laminar boundary layer.

8) Flutter of leaves

The effect of leaf-flutter on the transfer over leaves were studied by PARLANGE et al. (1971) and SCHUEPP (1972). SCHUEPP found that fluttering of leaves may increase the convection mass transfer coefficient by 40% as compared to the one for a rigid plate of leaf size and shape even in the case of fairly small intensity of turbulence. PARLANGE et al. suggested that fluttering has little effect on the transfer if the turbulence reaches a certain intensity. From these suggestions, it seems that the flutter effect may be considered as the joint effect of the inclination of leaves to wind and the turbulence of air flow. But it is considered that there still remain several uncertainties concerning the effect of the movement of a leaf on the boundary-layer transfer over the surface.

The literature survey described above suggests that main factors affecting the heat or mass transfer coefficient of forced convection through the boundary layer over a plant leaf under natural conditions may be the variation of temperature or mass concentration on the surface and the turbulent air flow within canopies, where is a joint effect of pressure gradient on the surface resulting from the inclination of the leaf to wind and flow-turbulence, or flutter of leaves.

Now, consider a leaf-shaped plate with 5 cm length along the flow direction. In the case of wind speed of a few meters per second, the surface temperature at the middle portion of the plate varies with nearly the 0.4-th power of the distance downstream from the leading edge of the surface under usual field conditions (TAKECHI, 1973). The exponent to the downwind distance in the vapor concentration distribution corresponding to the above temperature variation is about 0.25 (TAKECHI and HASEBA, 1973). The average vapor transfer coefficient is affected by such vapor concentration distribution and exceeds that for a plate with uniform concentration (or temperature) by a factor of about 1.2. An increase in the transfer coefficient for the plate within a canopy (for example, citrus) with leaf area density of 0.25 cm²/cm³ is as high as a factor of 1.3 (HASEBA, 1973b). Since both effect can be multiplied, the average transfer coefficient on the horizontal leaf-shaped plate within the canopy is 1.6 (=1.2x1.3) times larger than the one obtained from the laminar boundary-layer theory for an isothermal flat plate in parallel with air flow. Yet, the increment factor of the transfer coefficient may not reach to the value reported previously for real plant leaves, even with the addition of the other factors having a little effect. This indicates that the coefficient of vapor transfer obtained for the leaf shaped plate with the whole surface wetted may not be suitable to estimate the transfer from a plant leaf. Therefore, it is necessary to examine mass transfer from or to a flat plate with scattered sources or sinks similar to the leaf stomates.
3. Experiments and analyses on evaporation from flat plates with scattered evaporation sources

1) Experimental procedure

A flat rectangular plate with several separated wet strips as shown in Fig. 1 was used as a preliminary simple leaf-model in this section. The length of the plate along the air flow is L, and its width was chosen as a size for experimental convenience. The strips were cut to desired size whose length along the flow is b, and arrayed across the flow at equal interval, a.

Fig. 1. Schematic illustration of the plate with wet strips which is hatched.

Evaporation from the plate set in parallel with the air flow was measured by weighing method for the wind speeds between 0.5 and 8 m/s at the test section of a wind tunnel. The intensity of the flow-turbulence was below 1% of mean flow.

Average forced-convection vapor transfer coefficient \( D_B' \) for the plate was obtained through the following formula, after subtracting the buoyancy effect:

\[ w_T' = D_B' \frac{\partial C'}{\partial x}, \]

where \( w_T' \) = vapor flux density and the area used here is that of the plate, \( \partial C'/\partial x \) = water-vapor concentration difference between the surface and the air outside the boundary layer.

Here, the transfer coefficient \( D_B' \) would be equal to that for a plant leaf \( D_B \), if the wet sources having the same sizes as leaf stomates are distributed in the same density.

2) Overlapping of individual boundary layer of vapor concentration

Fig. 2 shows the relation between the average coefficient \( D_B' \) of vapor transfer from the plate and wind speed \( u \), for \( N=1, 2, 3, \) and 5, where \( N \) denotes the numbers of wet strips of 1 cm length which are separated by 1 cm interval. The obtained forced-convection transfer coefficient is proportional to the 0.5-th power of wind speed. Accordingly, the boundary layer flow in this experiment seems to be laminar. Similar results were obtained for a plate with strips of 0.5 cm in both wet length and interval. In these cases, the surface-temperature variation could be neglected, since the plate was not heated (HASEBA, 1973a).

Fig. 2. Relations between average forced-convection water-vapor transfer coefficient \( D_B' \) for a rectangular plate with separated evaporation sources of 1 cm in both wet length and interval and wind speed \( u \), for various numbers \( N \) of wet strips.

It will be discussed later that the numerical coefficient of \( D_B' \) decreases with an increase in the numbers of strips.

Next consideration would be a rectangular plate with unit width and length \( L \) along air-flow, on which the wet strips with unit width and wet length \( b \) in wind direction are arranged at interval \( a \). The surface-temperature is assumed to be uniform in this case. In order to obtain the vapor transfer coefficient across the laminar boundary-layer on the \( i \)-th strip, the theory of the heat transfer from a plate with an unheated starting section has been applied. Local vapor transfer coefficient \( D_{i,x} \), when the effect of the vapor transported from the windward sources is not taken into account, is written as follows (ECKERT and DRAKE, 1959):

\[ D_{i,x} = A \left\{ \frac{1}{x_{1/4}} - \frac{1}{x_{3/4}} \right\}, \]

where \( A = 0.332 \sqrt{Sc} \left( \frac{1}{x_{3/4}} - \frac{1}{x_{1/4}} \right) \),

\( Sc = \frac{d}{\nu} \),

\( d \) = molecular diffusion coefficient of water-vapor into air, \( \nu \) = dynamic viscosity of air, \( x \) = downstream distance over the surface from the leading edge.

From the above equation, the average transfer coeffi-
cient $D_i$ on the $i$-th strip can be obtained in the following formula:

$$D_i = \frac{2A}{b} \left\{ \left( \frac{x_i + b}{b} \right)^{3/4} - \frac{x_i^{3/4}}{2} \right\}^{2/3}. \quad (2)$$

When there are $N$ strips along the plate length of $L$, and is a non-evaporation starting section with length $a$ at the leading edge, it follows that $L = Na + b$, and $x_i = i(a + b) - b$. After defining the relative spacing $\delta$ between neighboring strips, $\delta = (a + b)/b$, equation (2) is rewritten:

$$D_i = \frac{2A(\delta/b)^{1/2} i^{1/2} \left\{ 1 - \left(1 - \frac{1}{i \delta} \right)^{3/4} \right\}^{2/3}}. \quad (3)$$

On the other hand, the average forced-convection transfer coefficient $D_{BW}$ for a rectangular plate with the length of $L$, the whole surface of which is wetted, is given in the form:

$$D_{BW} = 2AL^{-1/2}. \quad (4)$$

The ratio $\alpha_i$ of $D_i$ to $D_{BW}$ is derived from equations (3) and (4):

$$\alpha_i = \frac{D_i}{D_{BW}} = \left( \frac{\delta}{b} \right)^{1/2} \left\{ 1 - \left(1 - \frac{1}{i \delta} \right)^{3/4} \right\}^{2/3}.$$

Vapor flux $W_i$ from the $i$-th wet strip on the plate surface may be written as follows:

$$W_i = \tau_i D_i \Delta C_i s,$$

where $s =$area of a strip, now $s = b$, and $\tau_i =$factor presenting the effect of the overlapping of the boundary-layer on the transfer from the individual source.

In the analysis of the overlapping effect, the variation in the vapor difference $\Delta C_i$ for the individual strip is an essential problem. It is, however, so difficult to measure each concentration difference that the effect of the boundary-layer overlapping is taken into account in the present study through a universal multiplication factor $\tau$ on the transfer coefficient and constant concentration difference $\Delta C$. Vapor flux $W_T^\prime$ from the whole surface of the rectangular plate with discontinuous evaporation sources and flux density $w_T^\prime$ are given respectively as follows:

$$W_T^\prime = \Sigma W_i = (\Sigma \tau_i D_i) \Delta C \cdot s,$$

$$w_T^\prime = W_T^\prime / S = \frac{\Sigma \tau_i D_i \Delta C \cdot s}{S}, \quad (6)$$

where $S =$area of the plate.

Comparison of the equation (1) with (6) leads to the following equation:

$$D_T^\prime = \frac{\delta}{S} \Sigma \tau_i D_i \left( \frac{b}{\Sigma \tau_i D_i} \Sigma \tau_i D_i = \frac{\Sigma \tau_i D_i}{(N + 1) \delta - 1} \right).$$

Using the equation (5), the above equation is rewritten:

$$D_T^\prime = \frac{\Sigma \tau_i \alpha_i D_{BW} / \left( (N + 1) \delta - 1 \right)}.$$

A universal factor $\tau$ expressing the total effect of the overlapping of the boundary layers may be defined out of the summation in the following formula:

$$D_T^\prime = \tau D_{BW} \Sigma \alpha_i / \left( (N + 1) \delta - 1 \right). \quad \text{(7)}$$

When $\tau = 1$, i.e. if there is no effect of the overlapping, equation (7) yields

$$D_T^\prime / D_{BW} = \Sigma \alpha_i / \left( (N + 1) \delta - 1 \right).$$

Therefore, an empirical factor $\tau$ is given by the comparison between $D_T^\prime / D_{BW}$ obtained from experiments and the calculated value of $\Sigma \alpha_i / \left( (N + 1) \delta - 1 \right)$,

$$\tau = \frac{D_T^\prime / D_{BW}}{\Sigma \alpha_i / \left( (N + 1) \delta - 1 \right)}.$$
layer increased with increasing number of the wet strips, i.e. \( \tau \) becomes smaller than unity.

Next, a decrease in the rate of transfer owing to the effect of the boundary-layer overlapping was examined for the different relative spacings between strips. The rectangular plates, on the surface of which two wet strips were arranged in various spacings, were used to obtain the relation between the factor \( \tau \) and the spacing.

It is apparent from Fig. 4 that the effect of the boundary-layer overlapping vanishes if the spacing is ten times or more larger than the length of the wet strip.

![Fig. 4. Dependence of the factor (\( \tau \)) on the relative spacing (\( \delta \)) between evaporation sources, in the case of \( N=2 \).](image)

\( \delta = (a+b)/b \); points, \( b=1 \) cm; circles, \( b=0.5 \) cm.

(3) Forced-convection transfer of water vapor from a flat plate with separated evaporation sources

The average transfer coefficient \( D_{WB} \) for the plate with the separated evaporation sources was evaluated for different spacings \( \delta \) of wet strips. Evaporation from the plate with \( L=5 \) cm, \( a+b=1 \) cm and \( N=4 \) was measured for strip length \( b=1, 0.8, 0.6, 0.4, 0.2 \) and \( 0.1 \) cm. The average transfer coefficient obtained was proportional to the 1/2-th power of wind speed.

Fig. 5 shows the relation between the ratio \( D_{WB}/D_{BWP} \) and \( \delta \). In the figure, the upper solid line represents the relation calculated from the equation (7) with \( \tau =1 \). The average transfer coefficient decreases with decreasing dimension of evaporation source. When the spacing between strips was smaller, the observed value of \( D_{WB}/D_{BWP} \) was smaller than the theory because of the dominant effect of the overlapping. For the range of \( \delta \) greater than about 10, the observed ratio agrees well with the calculated value.

![Fig. 5. Comparison of the ratio (\( D_{WB}/D_{BWP} \)) between experimental results and the theoretical for \( \tau =1 \).](image)

4. Discussions

(1) Convective transfer coefficient for leaf-shaped plate with evaporation sources distributed with the spacing similar to the distance between the leaf stomates

Usually, the spacing of leaf stomates is about 10 times or more larger than the maximum stomatal dimension in the epidermis of common plants (Verduin, 1947). In such case, it may be reasonable to assume that, on the basis of the results obtained in the former section, the effect of the overlapping of the concentration boundary layer of individual stomate on the mass transfer is negligible.

The average vapor transfer coefficient \( D_i \) for each rectangular evaporation source which has the size \( b \times d \) and is distributed at the spacing of \( a+b \) on the flat surface with size \( L \times (c+d) \) shown in Fig. 6 is obtained as follows:

\[
D_i = \frac{1}{bd} \int_{x_1}^{x_2} \int_{y}^{y} D_{WB} \, dx \, dy
\]

\[
= 2A(b/d)^{1/2} (1 - 1 - (1 - 1) b^{3/4})^{2/3},
\]

where \( d \) is the width of the strip and \( c+d \) the width of the plate in the y-axis perpendicular to the air flow.

Vapor flux density \( w_{\tau} \) from each source is given as
follows:

\[ w' = \frac{1}{L(c+d)} \sum_{i=1}^{N} \frac{D_i d}{c} \cdot b \]

\[ = \frac{bd}{L(c+d)} \cdot C \cdot D_i \]

\[ = \frac{2Ab^1/2d}{L(c+d)} \delta^{1/2} A \cdot C \cdot \Sigma i^{1/2} \left[ 1 - \left(1 - \frac{1}{i \delta}\right)^{3/4}\right]^{2/3}. \]

It follows from the comparison of the above equation with equation (1) that the average transfer coefficient \(D_B'\) without both effects of the boundary-layer overlapping and the edge on the transfer from a very small surface is expressed by the following formula:

\[ D_B' = \frac{2A b^{1/2} d}{L(c+d)} \delta^{1/2} \cdot A \cdot C \cdot \Sigma i^{1/2} \left[ 1 - \left(1 - \frac{1}{i \delta}\right)^{3/4}\right]^{1/2}. \]

The average transfer coefficient \(D_{BW}\) of a flat plate with the size \(L(c+d)\) is derived from equation (5); namely,

\[ \frac{D_B'}{D_{BW}} = \left(\frac{c+d}{d} \cdot \frac{c+d}{b} \right)^{1/2} \delta^{1/2} \cdot \Sigma i^{1/2} \left[ 1 - \left(1 - \frac{1}{i \delta}\right)^{3/4}\right]^{2/3}. \]

With the definition \(\frac{c+d}{d} \cdot \frac{c+d}{b} = \delta\), the following relation is obtained:

\[ \frac{D_B'}{D_{BW}} = \delta^{3/2} \cdot \Sigma i^{1/2} \left[ 1 - \left(1 - \frac{1}{i \delta}\right)^{3/4}\right]^{2/3} \delta(N+1-1/\delta)^{1/2}. \]

The relation between the ratio \(D_B'/D_{BW}\) calculated through the above equation and the number \(N\) of wet portions, are represented in Fig. 6, where the relative spacing \(\delta\) between evaporation sources is taken as a parameter.

In the case of a leaf with stomatal aperture 10 \(\mu\)m and stomatal spacing 100 \(\mu\)m, there are about 1,000 evaporation-sources in the leaf of 10 cm long. Since \(\delta\) is equal to 10, it is clear in Fig. 6 that the ratio \(D_B'/D_{BW}\) is approximately 0.2. Thus it would be concluded that the average vapor transfer coefficient for such a leaf is smaller by a factor of 0.2 as compared with that for a plate with the same size and the whole surface wetted. When \(\delta\) becomes larger at stomatal closing, the transfer coefficient could be reduced more. For instance, the ratio of the former coefficient to the latter is about 0.0045 in the case of 1 \(\mu\)m source-dimension and spacing of 100 source-dimensions.

(2) Edge effect on boundary-layer transfer from a small object

The transfer from or to the surface of small plate with dimension of the order of \(\mu\)m in uniform flow is influenced by the following factors: (1) the molecular diffusion in the direction of air flow, (2) the change in the velocity gradient in the vicinity of the edge of the boundary layer and (3) the change in the pattern of the flow velocity due to the wake behind the edge. HIJIKATA et al. (1972) reported about the nature of forced-convection heat transfer in the vicinity of the leading edge of a rectangular plate in the parallel air flow, and HIJIKATA and MORI (1971) showed the results of analysis of the transfer in the vicinity of the trailing edge.

Fig. 7 shows the relation between the ratio of local transfer coefficient \(D_x\) to the average \(D_{BW}\) and the local Reynolds number \(Re_x\). This is prepared based on the results by HIJIKATA et al., and the Reynolds number with the plate dimension \(Re_{L}\) is 10 and 100. In the figure, downstream distance \(x\) from the leading edge for the wind speed of 1 m/s are also represented in the upper abscissa.

In Fig. 8, the relation between the ratio of the local transfer coefficient in the vicinity of the trailing edge of a plate with \(L=10\) cm to the average transfer coefficient and the distance from the trailing edge, \(L-x\) are presented for various wind speeds. Data are taken from the
leading and trailing edges that a factor of up to 2 may be assigned to the side effect. The effect from both sides of the plate is, therefore, represented by a factor of 4. Accordingly, a factor for the total edge effect on the transfer from the surface of 10 μm length may be evaluated to be about 12 (=3×4).

(3) Transfer coefficients for a plant leaf and for a leaf-shaped plate

If leaf stomates are separated from each other at the spacing which is large enough to neglect the effect of the overlapping of the boundary layer for vapor concentration, the forced-convection mass transfer coefficient for plant leaf $D_B$ may be about 2 times ($=0.2×3×4$) greater than that for a leaf-shaped plate with the whole surface wetted. The numerals were taken from the result obtained in the former sections. In this estimate, the effect of the separation of evaporation sources with very small dimension and that of the edge of the wet source are multiplied. In the field, the transfer coefficient becomes larger than the value estimated above in addition of the effects of the vapor-concentration variation over the leaf-surface and the flow-turbulence within a canopy or leaf fluttering.

Then, the value of the ratio $D_B/D_{BW}$ can be reduced by stomatal closing. In this case, according to an increase in the value of $\delta$ the transfer coefficient for a leaf $D_B$ may become smaller than that for a leaf-shaped plate $D_{BW}$. Therefore, the large values of “leaf-transfer-coefficient” reported by Hunt et al. (1968) and Kanemasu et al. (1969) might be obtained in the case of relatively large opening of stomates or of small spacing between stomates.

An “internal-transfer-coefficient” $D_L$ for vapor transfer through stomates, which appears in the “transpiration-transfer-coefficient” defined by Haseba and Takechi (1972), is related to stomatal aperture, while leaf-transfer-coefficient $D_B$ discussed here is a function of the aperture and also of distribution of stomates. Since both coefficients are related to the stomatal aperture, a combined treatment of $D_B$ and $D_L$ is not simple. Therefore, it may be practical to assume that the leaf boundary-layer transfer coefficient is related to the coefficient for a leaf-shaped plate with whole surface wetted and, accordingly, $D_L$ is taken as an apparent coefficient.
5. Conclusions

The vapor transfer from small evaporation sources at the surface of a plate in parallel with air flow is affected little by the vapor-concentration boundary-layer established at the upstream sources, if the spacing between the sources is more than ten times the source-dimension.

The average transfer coefficient for a rectangular plate, on which the evaporation sources are given by the wet strips separated in the direction of air flow, has been obtained as a function of the number of the strips for various spacings between strips. In this case, the effects of the boundary-layer overlapping and of the transfer in the vicinity of the edge of a small evaporation source are ignored. For example, the average transfer coefficient for a plate, where 1,000 sources of 10 μm dimension are arranged at 100 μm spacing along the flow direction, is reduced by a factor of about 0.2 compared with that for the wet plate with the same length, 10 cm. The ratio of the former coefficient to the latter decreases with a decrease in source-dimension.

However, if the edge effect on the transfer from a very small source is added to the effect mentioned above, the average transfer coefficient for a leaf with stomates of the actually maximum opening-dimension and spacing of about ten dimensions may become substantially larger than the coefficient obtained from the application of the boundary layer theory to a leaf-shaped plate with the whole surface wetted.

References

9) HASEBA, T. and TAKECHI, O. 1973: Local water-vapor transfer coefficient on horizontal leaf-shaped plane surface under field conditions. Ibid., 28, 149–155.*
葉面における物質輸送に関する研究（1）
不連続湿面からの水蒸気輸送—序報—

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植物葉面境界層における物質輸送を明らかにするための基礎的事項として、気流に平行な矩形平板上に並ぶ不連続湿面からの強制対流による水蒸気輸送について調べた。

風上側にある湿面の水蒸気濃度境界層が、風下側湿面における水蒸気輸送に及ぼす効果を、種々の湿面寸法と湿面間距離の場合について調べた。不連続湿面を持つ平板の輸送係数を無加熱の Starting Section がある平板の熱伝達理論から求めた。

さらに、上の解析結果に、微小面からの境界層輸送における層流効果を加え、気孔が不連続蒸発面であることを考えて、葉面の水蒸気輸送係数を推定した。植物葉面の輸送係数は、全表面が湿面の葉形平板の輸送係数より、数倍大きくなる可能性のあることが示された。

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