CONVECTIVE HEAT TRANSFER FROM NARROW LEAVES

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Summary

Convective heat transfer was measured from models of leaves of four species of arid-zone tree. The models were made of copper and were heated electrically. Measurements were made in still and moving air, and empirical expressions for the convective heat transfer coefficient h_c derived in each case. These expressions for h_c for still air differed from the simplified engineering formulae for flat plates. The four types of leaf, being small, long, and narrow, fell outside the range of sizes to which the simplified free convection formulae apply, and it was found that in each case the convective heat transfer was greater than the latter would predict.

The validity of the formulae derived from the copper models was checked by using them to calculate the convection term in complete energy balances measured for real single leaves of similar size and shape to the models.

I. INTRODUCTION

The process of convective heat transfer must be taken into account in any study of the interchange of energy between a plant and its environment. Previous studies have been concerned with finding a reliable method of estimating the convective heat exchange in particular cases, and studying the manner in which the convection term varies with changes in the environment, or with properties of the leaf.

Sensible heat transfer between a heated object and the fluid surrounding it takes place by a combination of conduction through the layer of fluid adjacent to the surface, and convective movement of the fluid. Considering these two processes together an overall heat transfer coefficient h_c may be defined as follows:

$$h_c = \Delta Q/\Delta T,$$

where ΔQ = rate of heat loss per unit surface area and ΔT = surface–fluid temperature difference. This heat transfer coefficient is a function of properties of the fluid and the heated object.

In the study of convective heat transfer, various dimensionless groups are commonly used to correlate the many variables in more convenient form. The following dimensionless groups will be used in this paper:

Nusselt number	$\mathrm{Nu} = h_c\bar{B}/k,$
Prandtl number	$\mathrm{Pr} = C_p\mu/k,$
Grashof number	$\mathrm{Gr} = \bar{B}^3\rho^2 g\beta\Delta T/\mu^2,$
Reynolds number	$\mathrm{Re} = \rho V\bar{B}/\mu,$

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where

$\bar{B}$ = "characteristic dimension" of object,
k = thermal conductivity of fluid,
C_p = specific heat at constant pressure of fluid,
μ = viscosity of fluid,
ρ = density of fluid,
g = acceleration due to gravity,
β = coefficient of expansion of fluid,
V = velocity of fluid.

These groups are related in the following ways. For free convection:

$$\mathrm{Nu} = C(\mathrm{Gr.Pr})^n,$$

that is

$$h_c\bar{B}/k = C[(\bar{B}^3\rho^2 g\beta\Delta T/\mu^2).(C_p\mu/k)]^n.$$

where C and n are constant. This may be rewritten so as to separate the terms which are properties of the fluid:

$$h_c\bar{B} = kC[(\rho^2 g\beta C_p/\mu k)]^n(\bar{B}^3\Delta T)^n,$$

or

$$h_c = K\bar{B}^{3n-1}\Delta T^n,$$

where

$$K = kC[(\rho^2 g\beta C_p/\mu k)]^n.$$

For forced convection:

$$\mathrm{Nu} = C(\mathrm{Re})^n.(\mathrm{Pr})^m,$$

that is

$$h_c\bar{B}/k = C[(\rho V\bar{B}/\mu)]^n[(C_p\mu/k)]^m,$$

where C, m, and n are constants. Rewriting, to separate the terms which are properties of the fluid:

$$h_c\bar{B} = kC[(\rho/\mu)]^n[(C_p\mu/k)]^m(V\bar{B})^n,$$

or

$$h_c = K\bar{B}^{n-1}V^n,$$

where

$$K = kC[(\rho/\mu)]^n[(C_p\mu/k)]^m.$$

When the fluid surrounding the objects is air, the known properties of air may be substituted in the expressions for K, giving simplified expressions for h_c. Semi-empirical relationships among the dimensionless groups are given below for rectangular flat plates in air (Kreith 1965), and from these the corresponding expressions for h_c derived using properties of air at 25°C and normal atmospheric pressure.

For free convection in the range $10^4 < \mathrm{Gr.Pr} < 10^8$:

(1) Horizontal plate warmer than air, upper surface

$$\mathrm{Nu} = 0\cdot54\,(\mathrm{Gr}\,.\,\mathrm{Pr})^{\frac{1}{4}}$$

$$\therefore h_c = 6\cdot31\times10^{-3}\,(\Delta T/\bar{B})^{\frac{1}{4}}\ \mathrm{cal\ cm^{-2}\ min^{-1}\ degC^{-1}}.$$

(2) Horizontal plate warmer than air, lower surface

$$\mathrm{Nu} = 0\cdot27\,(\mathrm{Gr}\,.\,\mathrm{Pr})^{\frac{1}{4}}$$

$$\therefore h_c = 3\cdot15\times10^{-3}(\Delta T/\bar{B})^{\frac{1}{4}}\ \mathrm{cal\ cm^{-2}\ min^{-1}\ degC^{-1}}.$$

(3) Vertical plate

$$\mathrm{Nu} = 0\cdot516\,(\mathrm{Gr}\,.\,\mathrm{Pr})^{\frac{1}{4}}$$

$$\therefore h_c = 6\cdot03\times10^{-3}(\Delta T/\bar{B})^{\frac{1}{4}}\ \mathrm{cal\ cm^{-2}\ min^{-1}\ degC^{-1}}.$$

For forced convection in laminar flow, $\mathrm{Re} < 10^5$:

(4) Wind moving parallel to a plate with uniform-temperature surface

$$\mathrm{Nu} = 0\cdot664\,\mathrm{Re}^{\frac{1}{2}}\,\mathrm{Pr}^{\frac{1}{3}}$$

$$\therefore h_c = 5\cdot61\times10^{-3}(V/\bar{B})^{\frac{1}{2}}\ \mathrm{cal\ cm^{-2}\ min^{-1}\ degC^{-1}}.$$

These formulae have been used to calculate the convection from leaves which approximate to flat plates, e.g. Wolpert (1962), Gates (1963), but in several studies direct measurements have also been made to obtain experimental values of h_c for leaves. Linacre (1964) summarized two possible classes of approach to this problem, namely steady-state and unsteady-state methods, and outlined a simple method of the latter type based on measurements of the rate of cooling of a suddenly shaded leaf.

This method gave values of h_c in the range $0\cdot01$–$0\cdot05$ cal cm^{-2} min^{-1} degC^{-1}, which were of the same order of magnitude as other published results. The analysis was further developed by Linacre in a later paper (Linacre 1967). Forms of the cooling curve method have been used by Waggoner and Shaw (1952), Turrell, Austin, and Perry (1962), and Pearman (1965).

Gates and Benedict (1963) used a method involving schlieren photography to calculate convective heat loss from leaves of deciduous species, of characteristic dimension ranging from $1\cdot7$ to 20 cm. For the larger leaves the measured rates of convective heat loss agreed well with those calculated using the simplified flat-plate formulae, but some of the measured rates for one of the smaller leaves were up to twice those calculated.

Knoerr and Gay (1965), working with leaves having characteristic dimensions ranging from 7 to 11 cm, found that the experimental values of h_c agreed well with those calculated from the standard formulae for moving air, but that in still air, the smallest leaf had a value about twice the theoretical one. Tibbals *et al.* (1964) and Gates, Tibbals, and Kreith (1965) used silver casts of small conifer branches to determine values for these highly irregular shapes, which were in reasonable agreement with published data for banks of parallel tubes.

These various tests of the applicability of simplified engineering formulae indicate that the flat-plate formulae can indeed be satisfactorily applied to broad leaves, while conifer needles may be approximated by banks of cylinders; Pearman (1965) also found good agreement between standard formulae for cylinders and empirical values for succulent *Carpobrotus* leaves, which are triangular in cross-section. However, Thomas (1965) pointed out that the dimensions of small leaves may fall outside the range within which these formulae apply, and that experimental values of h_c should be determined for such leaves.

Thomas was concerned with heat transfer from the almost circular juvenile leaves of two species of eucalypt, and used a circular brass disk 2 cm in diameter as an approximate model of the leaves. The disk could be heated with an internal heating coil, and convective heat transfer from it was measured in still and moving air. The convective heat transfer per unit area of the disk was considerably greater than would have been predicted from the simplified formulae for a flat plate, and thus it was suggested that convection would play an increasingly important part in the energy balance of leaves of this small size.

Following Thomas's work with the 2-cm brass disk it was decided to use the same method to measure the heat transfer coefficient of a range of plates approximating the shapes of leaves of several arid-zone species, which are characteristically small and elongated with dimensions falling outside the range over which the standard formulae apply. From the results empirical expressions for h_c were derived for comparison with the standard formulae.

There are clearly limitations in applying formulae derived from measurements on metal plates to real leaves. To check the validity of the derived expressions, complete energy balances were measured for a series of real leaves, and the estimated convective heat transfer term compared with that calculated using the formulae derived from the metal plates.

II. Methods

The species used for comparison were: *Eucalyptus oleosa* F. Muell., *Heterodendrum oleaefolium*, Desf., *Myoporum platycarpum* R. Br., and *Acacia oswaldii* F. Muell.; these four occur in similar habitats in northern South Australia. Their leaves are approximately similar in shape, decreasing in size from *E. oleosa*, with mean length approximately 8 cm, to *A. oswaldii*, approximately 4 cm.

Four copper model leaves were made on the same principle as the brass disk of Thomas, to dimensions typical of a representative sample of leaves of each species, as indicated in the following tabulation:

Species	Model No.	Length, L (cm)	Mean Breadth, B (cm)	Area (cm^2)
E. oleosa	1	8·02	1·18	8·2
H. oleaefolium	2	6·53	0·76	4·6
M. platycarpum	3	5·64	0·60	3·2
A. oswaldii	4	4·19	0·44	1·7

Each "leaf" consisted of two sheets of thin copper, thickness 0·21 mm, with a loop of heater wire and a thermocouple mounted between them, and held together with epoxy resin (see Fig. 1). All lead wires from the leaf lamina ran through a 3 by $\frac{1}{8}$ in. ceramic insulator to which the lamina was glued and which acted as a "petiole".

On completion of each leaf model the resistance of the heater loop was measured, and corrected for the resistance of the copper lead wires to give the true resistance of the heater alone.

The thermocouple calibrations were checked over the range 20–70°C, and found to be in agreement with standard tables for copper–constantan as given in the 43rd edition of "Handbook of Chemistry and Physics" (Chemical Rubber Publ. Co., 1961), with a variation of up to 1 degC above 30°C. The heater resistances were also checked for possible variations with temperature over the same range, but were found to be constant to $\pm 0 \cdot 01$ ohm. The copper laminae were kept highly polished throughout the experiments to reduce heat loss by radiation. The emissivity of polished copper was taken as 0·03 from the "American Institute of Physics Handbook" (McGraw-Hill Book Co., 1957) and radiation losses were calculated using this value.

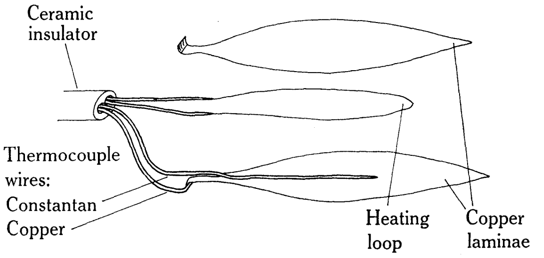

Fig. 1.—Construction details of leaf model.

Two series of experiments were carried out, the first in still, the second in moving air. For the still-air series, the models were set up inside a growth cabinet with lights off and internal temperature close to ambient. Air temperature was read with a mercury thermometer hung close to the leaves, and a thermocouple mounted beside them; these usually differed by 0·2–0·4 degC, and the mean was taken. The thermometer could be read through the glass doors of the cabinet, without disturbing the equilibrium conditions inside.

For the moving-air experiments a small wind tunnel was used; dimensions of the experimental chamber of the tunnel were 1·5 by 1 ft by 2·5 in. Leaf models were mounted across this section, with the air temperature thermometer set horizontally at the bottom of the chamber. Air velocity was measured with a Pitot tube, the pressure difference being read with a Chattock–Fry tilting manometer. Air velocity was measured over the range 0–1000 cm sec^{-1}, with an accuracy of ± 40 cm sec^{-1} at the lower speeds. The wind-tunnel motor was supplied from a 240-V d.c. stabilized power supply, but mains fluctuations caused a certain amount of instability, especially at the higher velocities.

To test the applicability of the derived formulae to real leaves a series of complete measurements of the energy balance of single leaves was carried out in a glasshouse. Leaves of *E. oleosa* and *M. platycarpum* were used, as trees of these species grew conveniently close to the laboratory. The petioles were cut under water and sealed into vinyl tubing, connecting the leaves to small potometers. The leaves were then mounted horizontally 20 cm above a large sand tray.

The components of the radiation flux were measured as follows: downward solar radiation S, with a Kipp solarimeter; solar radiation from the sand s, with a second Kipp solarimeter inverted; total downward radiation, with a CSIRO model CN–2 portable net radiometer (with unidirectional adaptor). These three sensors were mounted close to, and at the same height as, the leaf. The upward long-wavelength radiation R_g was calculated from the surface temperature of the sand, measured with thermocouples. Downward long-wavelength radiation R_a was found by subtracting the short-wavelength component S from the net radiometer reading.

Leaf temperatures T_l were measured with fine (0·005 in.) stainless steel constantan thermocouples pressed to the upper and lower surfaces; air temperature by thermocouples mounted close to the leaves.

Wind speeds were varied by adjusting the fans of the glasshouse air-conditioning system. Four speeds were used, which were measured in a preliminary experiment by placing a Casella sensitive cup anemometer at the position to be occupied by the leaves.

All thermocouple and radiometer data were recorded by a Honeywell Type 153 Universal Electronik Multipoint recorder.

III. Results

(a) *Leaf Models in Still Air*

Rates of convective heat loss were determined for each leaf model in each of three orientations, viz: A, lamina horizontal; B, lamina vertical, long axis horizontal; C, lamina vertical, long axis vertical. It was considered that these three would give

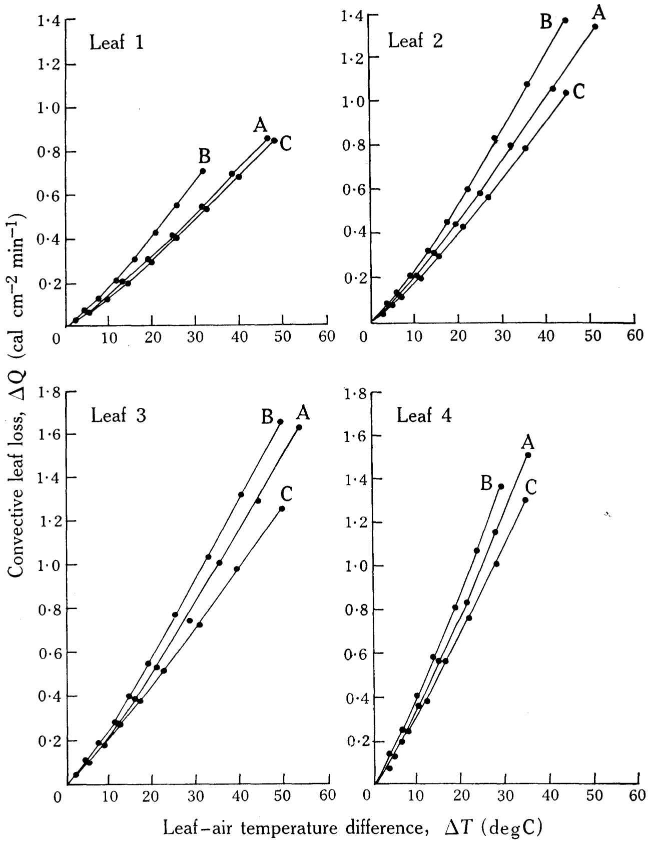

Fig. 2.—Convective heat loss ΔQ as a function of leaf–air temperature difference ΔT for leaves 1, 2, 3, and 4 respectively.

a fair indication of differences likely to occur between leaves at different orientations on a tree. However, further comment on the question of leaf orientation is given in Section IV.

The leaf model was set up in the cabinet and left for several hours to regain thermal equilibrium. After an initial reading of leaf and air temperature, the heater was switched on, voltage adjusted, and the leaf allowed to reach a new steady temperature. Readings of leaf temperature T_l, air temperature T_a, and heater voltage were then taken. The following energy balance terms could then be calculated:

- Q_h energy dissipated in the heater;
- Q_{Ri} radiation input, assuming the chamber to be acting as a black thermal cavity;
- Q_{Ro} radiation output, from known values of lamina temperature and emissivity;
- Q_c conduction along the ceramic "petiole". It was found that this term was appreciable, and subsidiary experiments were carried out to estimate it.

The difference between energy input and output, ΔQ, was given by

$$\Delta Q = (Q_h+Q_{Ri})-(Q_{Ro}+Q_c),$$

and this was assumed to be lost entirely by convection from the leaf. Figure 2 shows curves of ΔQ, the convective heat loss, against ΔT, the leaf–air temperature difference, for each of the four models in the three positions. From this data the heat transfer coefficient h_c was calculated for each level of heater input.

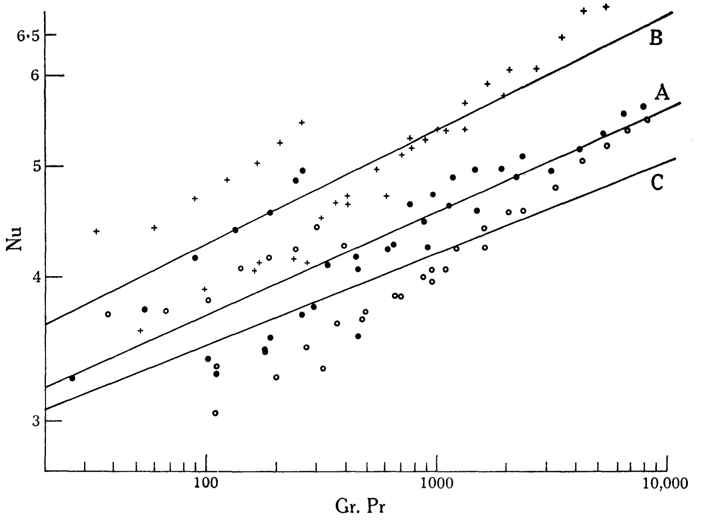

Fig. 3.—Still air data for all leaves. Values of Nusselt number Nu plotted against the product of Grashof number Gr and Prandtl number Pr, on logarithmic scales. ● Position A. + Position B. ○ Position C. The regression lines shown were calculated from all the data for each position.

The data from all four leaves were combined for each of the three positions, and Nusselt number Nu plotted against the product of Grashof and Prandtl numbers, as shown in Figure 3. Regression lines were calculated from the data for each position, and these are shown in the figure. Note that to find the most appropriate value for the characteristic dimension $\bar{B}$, each regression was calculated five times, giving $\bar{B}$ the values L, $\frac{3}{4}L+\frac{1}{4}B$, $\frac{1}{2}L+\frac{1}{2}B$, $\frac{1}{4}L+\frac{3}{4}B$, and B, where L and B were mean length and mean breadth of the leaf models. In each case, the correlation was best when $\bar{B} = B$, i.e. when the characteristic dimension was taken as the mean breadth alone.

The regression lines had the following equations:

Position A	$\mathrm{Nu} = 2 \cdot 44(\mathrm{Gr} \, . \, \mathrm{Pr})^{0 \cdot 09}$
Position B	$\mathrm{Nu} = 2 \cdot 65(\mathrm{Gr} \, . \, \mathrm{Pr})^{0 \cdot 10}$
Position C	$\mathrm{Nu} = 2 \cdot 37(\mathrm{Gr} \, . \, \mathrm{Pr})^{0 \cdot 08}$

The derived expressions for the convective heat transfer coefficient h_c (cal cm^{-2} min^{-1} degC^{-1}) for the leaf models in still air are given in the following tabulation.

Position A	$h_c = 0 \cdot 0137 \, B^{-0 \cdot 73} \, \Delta T^{0 \cdot 09}$
Position B	$h_c = 0 \cdot 0158 \, B^{-0 \cdot 69} \, \Delta T^{0 \cdot 10}$
Position C	$h_c = 0 \cdot 0129 \, B^{-0 \cdot 75} \, \Delta T^{0 \cdot 08}$

(*b*) *Leaf Models in Moving Air*

In the wind tunnel, only two orientations of the leaf were investigated, namely:

A—leaf horizontal, with air stream passing transversely across the lamina;

B—leaf vertical, axis horizontal, with air stream impinging normally upon the lamina.

The heater voltage was set to a predetermined level, and leaf and air temperatures measured at a series of wind speeds. From the readings taken, ΔT and ΔQ were calculated as before, and hence values derived for h_c at each wind speed.

The sharp decrease in lamina temperature with increasing wind speed is illustrated by Figure 4, which shows data for leaf model No. 2 for three heater voltages.

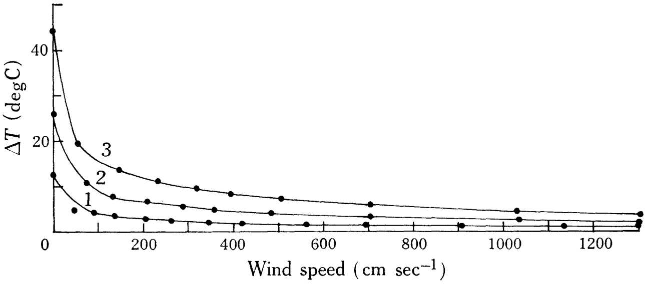

Fig. 4.—Leaf–air temperature difference ΔT plotted against wind speed for leaf model No. 2, at three heater voltages. Curve 1, 2 V; curve 2, 3 V; curve 3, 4 V.

The rate of decrease in temperature is greatest in the transition region between zero and low wind velocities. From a physiological point of view this is the most significant portion of the curves, and the region where wind-speed fluctuations have the greatest effect on leaf temperature.

In Figure 5 the Nusselt number Nu is plotted against Reynolds number Re, combining the data for all four leaves as in the still-air series. Regression lines were calculated for positions A and B, and these are shown in the figure. The same range of values as before was tried for $\bar{B}$ when calculating Nu, and again it was found that the correlation was best when $\bar{B} = B$, the mean breadth.

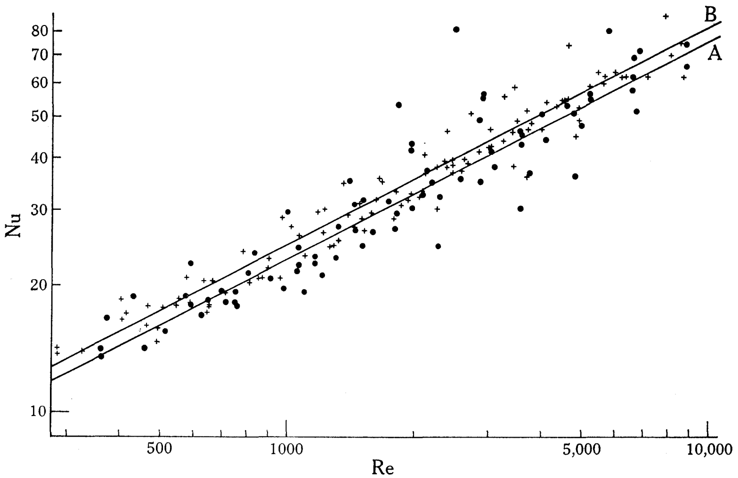

Fig. 5.—Moving air data for all leaves. Values of Nusselt number Nu plotted against Reynolds number Re, on logarithmic scales. ● Position A. + Position B. Regression lines shown were calculated from all the data for each position.

At the lowest wind speeds the readings appeared to be very scattered, so for purposes of the regression analysis all data for wind-speeds below 80 cm sec^{-1} were ignored. Hence the derived formulae only apply strictly to wind speeds greater than 80 cm sec^{-1}, i.e. 1·8 m.p.h.

The equations of the regression lines were:

Position A	$\mathrm{Nu} = 0\cdot632\ \mathrm{Re}^{0\cdot52}$
Position B	$\mathrm{Nu} = 0\cdot689\ \mathrm{Re}^{0\cdot52}$

The derived expressions for h_c, calculated using data from all four leaves in each position, are as follows:

Position A	$h_c = 0\cdot0062\ B^{-0\cdot48}\ V^{0\cdot52}$
Position B	$h_c = 0\cdot0067\ B^{-0\cdot48}\ V^{0\cdot52}$

(*c*) *Energy Balances of Real Leaves*

Several experiments on single "real" leaves were run in the glasshouse on different cloudless days, and sets of data to be used for calculating energy balances were chosen at times when conditions were steady. Three sizes of leaf were used, approximating to three of the four sizes of the copper leaf models. Leaf 1 was *E. oleosa*, leaves 2 and 3, *M. platycarpum*. The dimensions of the leaves were as follows:

Leaf	Length (cm)	Mean Breadth (cm)	Area* (cm^2)
1a	7·7	1·2	8·02
1b	9·2	1·2	9·90
2	6·0	0·8	4·20
3	4·4	0·6	2·31

* One surface.

In Table 1, summary energy balances are given at four wind speeds: 0, 93±8, 147±11, and 240±12 cm sec^{-1}. On the input side, the total radiation absorbed by

Table 1

SUMMARY OF ENERGY BALANCES FOR THREE SIZES OF LEAF, MEASURED IN STILL AIR AND AT THREE WIND SPEEDS

All energy terms have units cal/cm^2 of leaf lamina/min, i.e. they are fluxes of energy into or out of unit area of a leaf with two sides. For further explanation and for definition of symbols, see text

Leaf	Input			T_l (°C)	ΔT (degC)	h_c	Output				$2C'$
	$S+s$	R_a+R_g	Total				$2R_l$	Energy Loss by Transpiration	$2C$	Total	
					Still air						
1a	0·80	1·59	1·93	42·2	8·4	0·0145	1·57	0·09	0·24	1·90	0·27
2	1·07	1·51	1·99	44·0	7·9	0·0194	1·60	0·08	0·31	1·99	0·31
3	1·07	1·51	1·99	44·6	8·5	0·0250	1·61	0·00	0·42	2·03	0·38
					Wind speed = 93 cm sec^{-1}						
1b	1·10	1·48	1·97	38·1U	8·3U	0·060	1·48	0·06	0·94	2·48	0·43
				37·2L	7·4L						
2	0·91	1·33	1·74	27·3U	3·0U	0·073	1·27	0·12	0·30	1·69	0·35
				25·4L	1·1L						
3	0·91	1·33	1·74	28·6U	4·3U	0·086	1·30	0·00	0·59	1·89	0·44
				26·9L	2·6L						
					Wind speed = 147 cm sec^{-1}						
1b	1·33	1·65	2·25	38·8	9·6	0·076	1·50	0·05	1·46	3·01	0·70
2	0·70	1·64	1·92	29·1U	2·9U	0·092	1·31	0·10	0·41	1·82	0·51
				27·7L	1·5L						
3	0·70	1·64	1·92	30·6U	4·4U	0·109	1·33	0·00	0·87	2·20	0·59
				29·8L	3·6L						
					Wind speed = 240 cm sec^{-1}						
1b	0·69	1·53	1·82	31·1	2·1	0·098	1·35	0·15	0·41	1·91	0·32
2	1·14	1·38	1·89	29·9U	2·9U	0·119	1·31	0·12	0·46	1·89	0·46
				28·0L	1·0L						
3	1·14	1·38	1·89	29·7U	2·7U	0·140	1·31	0·00	0·56	1·87	0·58
				28·3L	1·3L						

the leaf was calculated assuming an absorption coefficient for solar radiation of 0·50, and for long-wave radiation of 0·96 (Gates and Tantraporn 1952). On the output side, re-radiation from the leaf R_l was calculated from the leaf surface temperature T_l. Where there were clear differences between upper and lower surfaces, these were treated separately; otherwise mean temperatures were used. Energy loss by transpiration was calculated from the potometer readings. Transpiration was low in all cases. For the eucalypt leaf in still air, a light coating of Vaseline was applied to reduce transpiration and hence increase leaf–air temperature difference, ΔT.

The values of h_c were calculated using the expressions given above for position A (leaf horizontal) in still air and moving air. These values of h_c were then used to calculate the convective heat loss C.

Note that the total energy input is given per square centimetre of a leaf with two sides. The units of R_l and C are cal cm^{-2} min^{-1} for one surface, and hence to give energy loss from a leaf section with two sides, their values must be doubled.

The last column of Table 1, headed $2C'$, gives values for convective heat loss obtained by subtracting the other output terms from the total input:

$$2C' = (\text{total input}) - (\text{radiation} + \text{transpiration output}).$$

If the balances were exact these values should be the same as those in the $2C$ column.

Estimated errors for the total input were 4–6%, and for the total output, 7–13%. The greatest errors occurred on the output side, in the estimates of air speed, 5–9%, and in the leaf–air temperature differences ΔT, where errors ranged from 13 to 60%, being greatest where ΔT was smallest. As both these terms affect convective heat loss C, the term being tested, the errors in C were rather large, ranging from 20 to 60%. By comparing the values of convective heat loss calculated from the formulae, and deduced from the energy balance (columns $2C$ and $2C'$, Table 1) it can be seen that within experimental error the two agree in all cases for leaf number 2, but that there are discrepancies for leaves 1 and 3 at the intermediate wind speeds.

IV. Discussion

The empirical formulae for h_c given above may be compared with the expressions quoted in the Introduction. The formula for position A in moving air is similar in form to that given for forced convection in laminar flow, with the plate parallel to the air stream. This would be expected, as the limiting condition for the standard formula is that $\mathrm{Re} < 10^5$ and this condition was fulfilled for all the leaf models in air.

The formula for position B is not very different from position A. Evidently the rate of convection was only slightly altered by orienting the lamina transverse, rather than parallel, to the air stream. However, Parkhurst *et al.* (1968) have shown that, depending on the shape of the lamina, the rate of convection may vary quite widely as the angle of orientation to the wind varies between 0 and 90°. In some cases they found that the rate was greater at intermediate angles than at either 0 or 90°; in other cases it was less. In the present series of measurements intermediate angles were not considered, but it is clear that they might be very important when dealing with real vegetation.

The formulae for still air differ markedly from the standard simplified free convection formulae quoted in the Introduction. The dependence of h_c upon the characteristic dimension is much greater, and the temperature dependence much less than in those simplified formulae. However, all points in Figure 3 lie below the range $10^4 < \mathrm{Gr} \cdot \mathrm{Pr} < 10^8$, within which the simplified formulae apply. In this lower range of Grashof numbers, the increase in convection with decreasing size of the object is more rapid than it is with larger objects.

The mean breadth of the lamina was found to be the most suitable dimension to use in calculating Nusselt numbers, both for free and forced convection. It appears that for such long, narrow shapes the length has very little influence on the rate of convection per unit area, even for free convection. Parkhurst *et al.* (1968) give a more elaborate method of calculating a characteristic dimension for an irregular object, but the method involves the assumption that the standard flat-plate formulae apply to the irregular shape, once its characteristic dimension is calculated. As the shapes used in this work were too small for this to be true, their method of calculating characteristic dimension was not used.

There are obvious differences between copper models and real leaves, and caution must be exercised in using these expressions for h_c in calculations involving the latter. Changes in surface texture may affect the boundary layer thickness; *E. oleosa* and *M. platycarpum* have relatively smooth leaves, but *A. oswaldii* is slightly ribbed, and *H. oleaefolium* is covered with a mat of short, fine hairs. The leaves, especially of *M. platycarpum*, are usually not exactly flat, and slight curvature may affect the air flow. As leaf tissue is a much poorer conductor of heat than metal, larger temperature differences may develop across leaf surfaces, which would complicate the convection process; and finally, interactions between leaves growing together in clusters of foliage would result in very different patterns from those of isolated leaves.

The results summarized in Table 1, however, indicate that the empirical formulae for h_c were adequate for each of the three sizes of leaf tested, in still air, and at the highest wind speed used (240 cm sec^{-1}). At the two intermediate wind speeds (93 and 147 cm sec^{-1}) there were discrepancies between input and calculated output for the smallest and largest leaves. It was pointed out above that the formulae for forced convection were valid only for wind speeds above 80 cm sec^{-1}, and although these two speeds were above this limit, they may still have been in the region where the formulae did not hold closely. The good agreement at 240 cm sec^{-1} suggests that the formulae may be reasonably accurate at higher wind speeds, but tend to overestimate convective heat losses at lower speeds.

The temperature and wind speed range over which the measurements on the models were made was greater than that likely to occur in real leaves. In fact the most significant portions of the curves from a biological point of view are just those where experimental errors are greatest, i.e. the low wind speeds and low values of ΔT. The readings were extended beyond what might be called the "physiological range", mainly in order to improve the curve plotting.

It would appear from these results that the formulae could be applied to single leaves which were isolated to some extent from the mass of foliage, to give at least the order of magnitude of convective heat transfer taking place. They could also be applied to leaves of other species of the same general size and shape. In general, the results emphasize the efficiency of small-area, narrow leaves in losing heat by convection, and the possible ecological importance of such leaves to plants growing under conditions of high temperature and high radiation.

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