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THE EVAPORATION OF WATER FROM *HELIX ASPERSA*

III. THE APPLICATION OF EVAPORATION FORMULAE

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INTRODUCTION

An attempt has been made, in the previous paper of this series (Machin, 1964), to relate evaporative water loss from the snail *Helix aspersa* to direct measurements of boundary-layer thickness. Since this method has proved only partially successful, a different approach was tried. The work presented here explores the possible application of mathematical formulae to evaporation from snails.

Evaporation formulae

Two formulae may be applied to evaporation in moving air where wind speeds are low enough for a stable laminar flow boundary layer to be set up. First, Jeffreys (1918) deduced, from a purely theoretical approach, that the total evaporation from a flat rectangular surface is given by the following equation:

$$E = 2\rho V_0 - V_d\sqrt{\frac{kv}{\pi}}\sqrt{x}.y, \tag{1}$$

where E is the mass of water evaporated in unit time, ρ is the density of air, V_0 is the concentration of water vapour at the evaporating surface, V_d is the concentration of water vapour of free air, k is the coefficient of diffusion of water vapour in air in units corresponding to V_0 and V_d, v is the wind speed of 'free' air, x is the length of surface in direction of wind, y is the breadth of surface. Ramsay (1935) may be criticized for extending the use of this formula to the evaporation from animals, on the following grounds:

(1) Jeffreys's formula applies strictly to flat evaporating surfaces. It has been shown (Machin, 1964) that the unstreamlined three-dimensional form of a snail produces irregularities in air flow which greatly influence the rate of evaporation. Since the above formula is based on the assumption that air flow over the evaporating surface is even and uninterrupted, it would be unwise to extend the use of the formula to snails or to any other animals whose body form is unstreamlined.

(2) Jeffreys limited the use of the formula to evaporating surfaces greater than 10 cm. in length in typical outdoor wind speeds of the order of 400 cm./sec. Most animals are less than 10 cm. long. Even in very low wind speeds, about 4 cm./sec., the minimum length of the evaporating surface is 1 cm., and would still exclude many species.

Furthermore, Jeffreys's formula is inconvenient in biological work since the terms

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V_0 and V_d, expressed as the mass of water vapour per unit volume of air, do not lend themselves to practical measurement. On the other hand, Leighly (1937) has devised a formula which not only is expressed in realistic and convenient units of vapour concentration, but may be applied to the more complex evaporation problems of animals and other three-dimensional surfaces. The formula is derived from the basic diffusion equation:

$$E = \frac{k(p_0 - p_d)}{D}, \tag{2}$$

where k is the coefficient of diffusion of water vapour, p_0 is the vapour pressure at the evaporating surface, p_d is the vapour pressure of ambient air, and D is the boundary-layer thickness. It is assumed by Leighly that the boundary-layer thickness cannot be measured directly and must therefore be substituted by an alternative expression. Boundary-layer thickness, he reasons, depends on four factors: the velocity of the wind, v; the length of the evaporating surface in the direction of the wind, x: and to a lesser extent the density of the air, ρ; and the molecular viscosity of air, μ. These may be combined to form the expression:

$$D \propto \sqrt{\frac{\mu}{\rho}} \cdot \left(\frac{x}{v}\right)^n. \tag{3}$$

It should be noted that this expression is in accordance with aerodynamic theory (Schlichting, 1955). Substituting in equation (2), Leighly's formula becomes:

$$E = k(p_0 - p_d)\, c \sqrt{\frac{\rho}{\mu}} \cdot \left(\frac{v}{x}\right)^n, \tag{4}$$

where c is the coefficient of proportionality. Since ρ and μ are constants, dependent on temperature and pressure, they may be conveniently combined with k to form a new constant, K. The formula therefore becomes:

$$E = K(p_0 - p_d)\, c \left(\frac{v}{x}\right)^n. \tag{5}$$

This form of the equation, where n and c are left for empirical determination, is particularly suitable for use with animals, whose complexity of form makes a purely theoretical approach impractical.

Martin (1943) has further developed Leighly's formula (5) for small rectangular surfaces and introduced a term showing variation with the dimension at right angles (y) to the wind direction. The formula he gives is:

$$E = K(p_o - p_d)\, cv^{0\cdot 5}/x^{0\cdot 3}y^{0\cdot 2}. \tag{6}$$

However, surface measurements of x and y in *Helix aspersa* are very similar and there is insufficient independent variation for equation (6) to apply. For the present study the two functions are more conveniently left combined as they are in formula (5).

MATERIALS AND METHODS

The experimental material used in this work, the method of estimating surface area and the experiments in room conditions, are identical to those described previously (Machin 1964). Length, x, used in the calculations properly refers to the maximum continuous length of moist skin measured along the dorsal surface of the animal. It does not refer to the overall length of the snail.

Further experiments were performed under controlled atmospheric conditions in a special chamber designed in the form of a small return-flow wind tunnel. The methods of temperature control and measurement in the chamber were based on those described by Beament (1958). Only those features which are unique to the apparatus used in the present work will be described here.

Wind-tunnel apparatus

Uniform air flow through the tunnel was ensured by a narrowing of the tunnel in the region where actual experimental determinations of evaporation were carried out. The proportions and layout of the tunnel, shown in Fig. 1, were designed so that the air had to pass through a maximum distance after it left the fan before reaching the experimental section. This, together with a length of aluminium honeycombing, helped to eliminate eddy currents in the air flow. The tunnel was provided with two brass stop-cocks for the introduction and escape of air, placed as far apart as possible to ensure efficient air replacement.

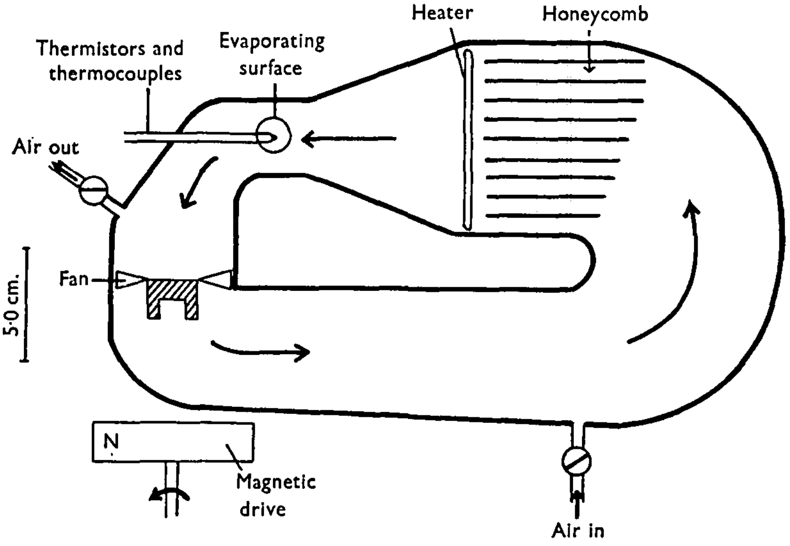

Fig. 1. Diagrammatic profile of wind tunnel.

Construction. The tunnel was constructed from a 3/16 in. sheet of 'Perspex'. All joints were sealed with 'Araldite' epoxy resin. A coating of polystyrene proved unsuccessful for rendering the internal surfaces water-repellent, so, instead, they were polished with silicone wax before assembly. All hatches were secured with brass screws and sealed with neoprene gaskets and silicone grease.

Circulation of air. The air was circulated in the tunnel by means of a magnetically driven 2 in. diameter fan which was mounted in self-lubricating phosphor-bronze bearings. A rheostat which permitted the motor speed to be varied was calibrated in terms of wind speed using the hot-wire anemometer probe placed centrally in the experimental section of the tunnel.

Construction and position of heater. The heater consisted of 60 ft. of 40 gauge nichrome wire with a total resistance of 2000 ohms. The wire was wound evenly spaced on parallel glass rods which fitted in a Perspex frame. This frame was slotted into the walls of the tunnel in such a way that the heater wire formed a double grille extending across that section of tunnel. The heater was positioned so that the air passed uninterrupted into the experimental part and immediately over the temperature-controlling thermistors, which were placed close together in the centre of the tunnel. Their temperature-sensitive tips were directly opposite the two openings designed to accommodate the Perspex clamps which held the experimental preparations. The most accurate control of temperature was obtained when the heat loading of the thermostat was minimal. This was achieved by housing the apparatus in a constant-temperature room adjusted to approximately 2° below the air temperature within the tunnel. Temperatures ranging from 4 to 20° C. could be controlled to an accuracy of ±0·1° C.

Control of atmospheric humidity. The following standard procedure was devised using porous earthenware evaporators in the control experiments to ensure that the wind tunnel contained thoroughly dried air before and during each experiment. Air which had been dried by passing it through a 36 in. column of fused $CaCl_2$ and two bottles of concentrated H_2SO_4 was pumped through the tunnel overnight. During the experiment the pumping rate was adjusted to a constant 1 l./min., the total volume of the apparatus being about 2 l. The tunnel thermostat was sufficiently sensitive to maintain a temperature of about 2° above ambient during the introduction of new dry air, without any loss in the accuracy of control. Anemometer measurements were unable to detect any variation in wind speed as a result of continuous pumping.

The possible effect of opening the tunnel for short periods of time so that experimental material could be introduced was also investigated. No change was observed, since the pumping of dry air through the tunnel caused an outward flow of air through the open aperture.

Experimental procedure

Evaporation measurements using disks of porous earthenware, rectangles of filter-paper (both soaked in distilled water) and freshly drowned *Helix aspersa* were made as follows.

After weighing on a balance accurate to 0·1 mg., kept in the constant-temperature room in which the experiment was carried out, the disks were placed in position in the side wall of the tunnel with the wetted surface facing outwards. The position of the cold junction of a thermocouple was previously adjusted so that it made contact with the centre of the disk. Surface-temperature measurements made in this way showed that there was an initial period in which the temperature dropped to a steady value. The time taken for this to occur depended on the rate of evaporation but never exceeded 5 min. The disk was left in position in the tunnel for a period of 30–40 min., during which time a continuous record of the surface temperature was made. The results were discarded of any experiment in which the temperature began to rise again, indicating that most of the distilled water had been lost from the disk. At the end of the experimental period the disk was removed and immediately reweighed. Errors due to the removal of the material before weighing were negligible because of the relatively small weight loss involved as compared to the large weight loss sustained during the full course of the experiment. The rate of evaporation from the disk over a wide range of different wind speeds and air temperatures was directly proportional to the difference between the steady surface temperature and that of air in the centre of the tunnel. Therefore it was considered that the errors due to the initial period of temperature equilibration were also negligible.

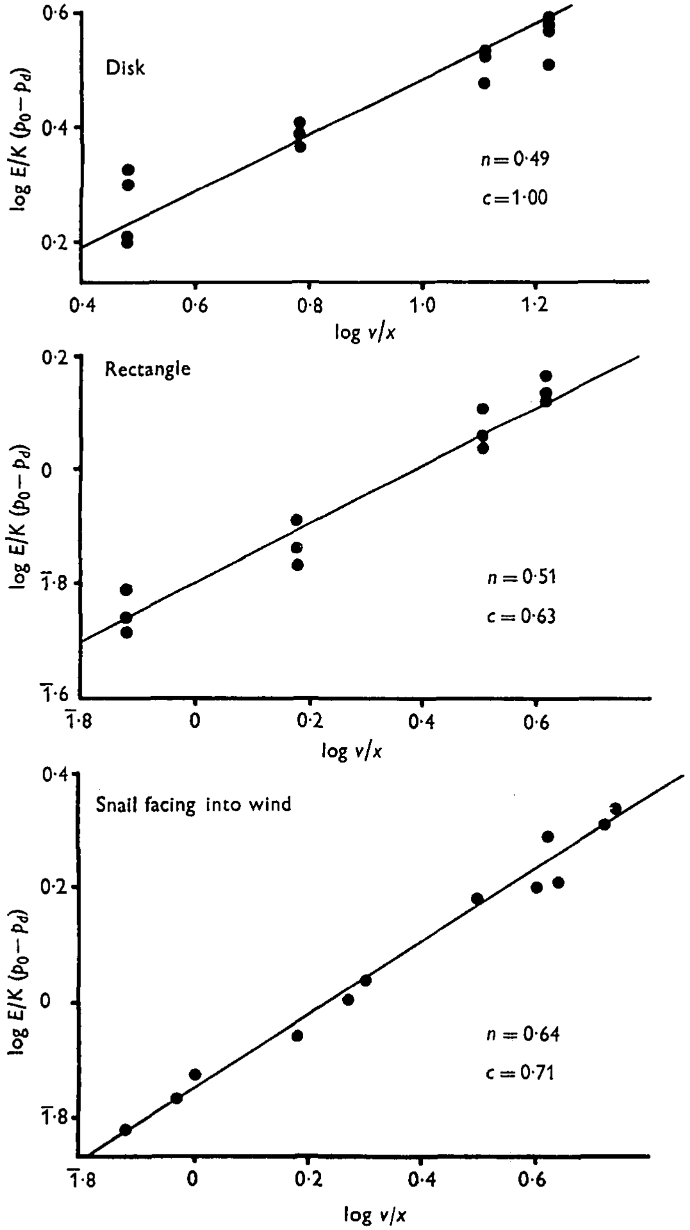

Fig. 2. Graphs of log $E/K(p_0-p_d)$ against log v/x for three different types of evaporator. The values of n and c calculated from each graph are also given. Measurements were made in the wind-tunnel apparatus.

Measurements of evaporative water loss were made with the rectangle of filter-paper placed on a slightly larger rectangle of waxed paper on the floor of the experimental section of the wind tunnel. Water loss was assessed as before by weighing at

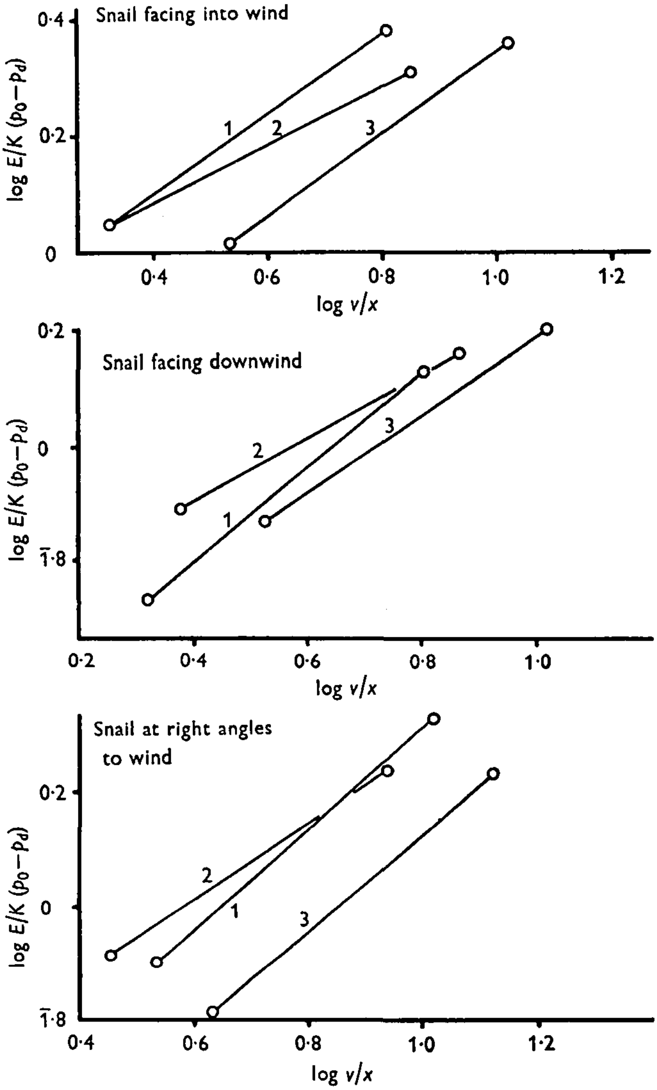

Fig. 3. Graphs of log $E/K(p_0 - p_d)$ against log v/x for the snail orientated in three different positions with respect to the wind. Straight lines have been drawn between corresponding pairs of determinations made with the same animal. The numbers identify the same animal in each graph. Measurements were made in room conditions.

the beginning and end of the experiment. Measurements of evaporative loss from freshly drowned snails were made in a similar way with the animal facing directly into the wind. One thermocouple was placed just beneath an optic tentacle of the snail and another on the dorsal surface of the body just under a lobe of the mantle.

RESULTS

The evaporation data obtained from the three different surfaces were used to determine the values of n and c in Leighly's formula (5). Since the form of the equation is of the type:

$$a = c\,.\,b^n,$$

or

$$\log a = \log c + n \log b,$$

where

$$a = E/K(p_0 - p_d) \quad \text{and} \quad b^n = (v/x)^n,$$

it follows that log a plotted against log b will give a straight line of slope n. Log c will be the 1·0 intercept on the a axis.

Table 1. *The values of c and n obtained from snails placed in different positions relative to the wind*

	Specimen no.	n	Mean n	c	Mean c
Snail facing into wind	1	0·67	0·62	0·66	0·67
	2	0·49		0·78	
	3	0·69		0·56	
Snail facing downwind	1	0·84	0·65	0·30	0·36
	2	0·55		0·46	
	3	0·67		0·32	
Snail at right angles to wind	1	0·67	0·69	0·41	0·29
	2	0·74		0·27	
	3	0·67		0·19	

It can be seen in Fig. 2 that Leighly's formula holds for all three evaporating surfaces since log $E/K(p_0 - p_d)$ against log v/x obtained from measurements made in the wind-tunnel apparatus are straight-line graphs. Surface-temperature measurements permitted corrections of p_0 due to evaporative cooling to be made. The values of n and c for each surface are given.

In Fig. 3 it is assumed Leighly's formula also holds, and accordingly straight lines have been drawn between corresponding pairs of determinations made with the same animal in each of three different positions. Here measurements were made in room conditions and no corrections of p_0 were possible. Individual values of n and c together with their calculated means are given in Table 1.

Calculations of n show that for flat evaporating surfaces (disk and rectangle) the evaporation rate varies very closely with the square root of the wind speed, since the linear dimensions of each remain constant. However, values of n are clearly greater in the case of the snail. There is good agreement between the measurements made with the snail facing into the wind under both sets of experimental conditions. 'Student's' t test indicated no significant difference between n with the snail in all three positions and between c with the snail facing downwind and at right angles to the wind. However, c with the snail facing into the wind was significantly different from the other two values to the 1% level. It can be seen in Fig. 2 that c values for the snail facing into the wind and for the rectangle of similar size agree fairly well.

DISCUSSION

It has been shown, with the terms *n* and *c* empirically determined for flat evaporating surfaces, that Leighly's formula is in accordance with well-established evaporation theory (Jeffreys, 1918; Leighly, 1937; Martin, 1943). Furthermore the expected differences in *n* and *c* due to variation in air flow over the snail, *Helix aspersa* (Machin, 1964) do in fact occur. Values of *n* and *c* determined for the snail differ significantly from those of flat surfaces and, in some cases also, when the snail is orientated differently to the wind. It is suggested therefore that the application of Leighly's formula is a useful and valid approach to the evaporation problems of terrestrial snails and perhaps of other moist-skinned animals.

The fact that *n* in the case of the snail is about 0·65 and is thus significantly greater than the 0·50 recorded for flat surfaces is an important one which supports the previous criticism of applying Jeffreys's formula to the evaporation of animals. Leighly (1937) reports a similar example in which *n* for a cylindrical object placed at right angles to the air flow is 0·7. The reason for this difference is that *n* expresses the rate at which boundary-layer thickness changes with v/x. Thus the boundary layer over a snail or similar three-dimensional object, due perhaps to a greater resistance to air flow, is thicker than that of a flat surface of similar size. In this context the direct measurements of boundary-layer thickness described in Machin (1964) provide a convenient criterion of 'unstreamlinedness' or the amount of air disturbance produced by the evaporating object. It was found that the mean boundary-layer thickness above the snail facing into the wind, away from and at right angles to it were 4·65, 13·6 and 5·75 mm., respectively. The corresponding value for a flat surface of similar size was only 3·0 mm. The value of *n* is therefore indicative of the form of the evaporating surface, although no significant difference between *n* with the snail orientated differently was established. This may be due to the inaccuracies of measurements made in room conditions.

Since a formula which includes *n* will hold only if boundary-layer thickness continues to change with v/x, it is possible that for very large evaporators boundary-layer thickness having reached a maximum will remain constant. Leighly (1937) was able to conclude that the upper limit of size lay between 1 and 26 m. on the grounds that data from an evaporator 26 m. in diameter did not fit the formula well. It is now possible using the data of Sleight, evidently unknown to Leighly, to estimate the limit at about 4 m. length. Sleight (1917) showed that differences in evaporation rate, attributed now to differences in boundary-layer thickness, could be measured in tanks of less than 4 m. diameter. No difference in evaporation rate could be detected between the 4 m. tank and a large lake. Martin (1943) has successfully applied Leighly's formula to the data of Sierp & Seybold (1927) and concluded that the formula holds for evaporators down to 1 mm. in length. Leighly's formula should therefore hold over the range of dimensions of most if not all moist-skinned animals.

It will be seen that coefficient *c* varies with the dimensions of the evaporating surface. The value for the flat disk of 1 cm. diameter is 1·00 but only 0·71 for the rectangle 4 cm. long. There is good agreement between the rectangle and *c* for the snail facing into the wind, where the snail's body is of similar length, and also with Martin's (1943) determination of *c* for flat surfaces which was 0·73. However, there are considerable differences between the snail facing into and away from the wind, where the length of evaporating surface is identical. In this case the position of the shell and its effect on boundary-layer thickness (see Machin, 1964) in these two positions must also be important in determining the value of c.

As a general rule it may be said that increased air resistance, which interferes with the normal pattern of air flow over an evaporating surface, is indicated by high values of n and low values of c. The combined determination of terms n and c for each evaporating surface, therefore, provides a relatively simple and convenient assessment of a complex three-dimensional form in terms of air flow and evaporation.

SUMMARY

1. The construction and use of a wind-tunnel apparatus is described in which measurements of evaporation under controlled conditions of temperature, humidity and air flow can be made.

2. Two mathematical formulae, applicable to evaporation in relatively low wind speeds, are described. It is suggested that a promising approach to evaporation from moist-skinned animals is provided by the application of Leighly's formula:

$$E = K(p_0 - p_d)c(v/x)^n,$$

where the rate of evaporation (E) is expressed in terms of the vapour pressure at the evaporating surface (p_0) and in the ambient air (p_d), the wind speed (v) and the length of the evaporating surface parallel to the wind (x). The constant, K, is calculated independently and the terms n and c are left for empirical determination.

3. Values of n and c for different types of evaporating surface are given together with the method used in their calculation. Those relating to flat evaporators and to the snail, *Helix aspersa*, are shown to differ significantly.

4. In general n increases and c decreases as the amount of air disturbance caused by the snail increases.

5. The fact that n for flat surfaces is in good agreement with previously established theory is taken as evidence that Leighly's formula may be validly applied.

6. The combined determination of n and c is introduced as a convenient assessment of a complex form in terms of air flow and evaporation.

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