THE INFLUENCE OF AIR MOVEMENT AND ATMOSPHERIC CONDITIONS ON THE HEAT LOSS FROM A CYLINDRICAL MOIST BODY

BY ALAN J. CANNY, M.D. AND C. J. MARTIN, M.B., D.SC., F.R.S.

From the Lister Institute of Preventive Medicine

(With 4 Figures in the Text)

PART I

THE observations to be described were undertaken to obtain data for applica tion to physiological problems.

With the small cylinder employed, which we dubbed "Homunculus" most of the thermic adjustments made by an animal could be imitated. Th heat produced in its interior was controllable. The rate at which heat wa transported to the surface could be modified either by altering the efficienc of the circulation, the conductivity of the liquid contents, or by interposing a layer of paraffin wax between the circulating fluid and the moistened covering so simulating fat deposition. The rate of heat loss by evaporation from th surface could be modified by the amount of water supplied to the covering.

The "homunculus" also lends itself to the study of the effect of clothing of various texture and composition on heat transfer by convection, radiatio and evaporation, but this aspect of the enquiry is not dealt with in the presen paper.

To what extent the laws governing different kinds of heat loss from th particular system studied would be applicable to other systems, we wer doubtful, and we fully appreciated that their application to, say, the huma body would be complicated by the physiological adjustments.

However, these limitations did not deter us, for in the study of such physiological adjustments it is essential to understand what physical principles are being taken advantage of and, as far as possible, their quantitative significance.

From theoretical considerations assuming stream-line flow over a body whose surface temperature is kept constant, Boussinesq (1901) concluded that the loss of heat should be directly proportional to the temperature excess of the surface above that of the surrounding fluid measured at a distance, and also to the square root of the velocity of the fluid current. Russell (1910) treated the case of a cylinder over which the flow was a stream-line. His conclusions are the same as those of Boussinesq. Von Schuckmann (1904), Heymann (1904), King (1914), and Hill *et al.* (1916) found experimentally that the rate of heat loss from various simple systems was proportional to the square root of the wind velocity, although only King's experiments on the loss of heat from fine platinum wires moving in air satisfied

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the ideal conditions assumed by Boussinesq. Later, Hill *et al.* (1922) pointed out that at velocities below 1 m./sec., this relation between heat loss and wind speed was disturbed by natural convection currents. The above authors have dealt only with dry bodies.

The relation between wind velocity and evaporation of ether and of water from cylindrical vessels was studied by Schierbeck (1895). He found a direct proportionality between evaporation and the square root of the velocity. His paper includes a critical discussion of earlier work.

From their experiments, Hill *et al.* (1916) concluded that loss of heat by evaporation from Hill's katathermometer was also proportional to the square root of the wind velocity. They regarded the difference in heat lost in unit time by the wet katathermometer and that lost by the dry katathermometer cooling over the same range of temperature, as loss from evaporation. This seems hardly justified, as the temperature and emissivity of the surface would be different in the two cases. As a result of further experiments, Hill *et al.* (1922) decided that the substitution of the cube root of the velocity for the square root function in the earlier equation resulted in more satisfactory agreement with the later observations. Rees (1927) concluded that Hill's wet katathermometer cools at a rate proportional to the square root of the wind velocity, but his observations seem to us to fit better a cube root relationship.

Most of the previous investigators of heat loss in wind currents have not taken into account the complicating effect of concomitant change of surface temperature. Only when the temperature of the surface of the system remains constant can the real effect of variation in the air movement upon the rate of cooling be directly determined. The theoretical treatment of the subject has assumed such constancy, but, in practice, this condition is not usually fulfilled for alteration in the rate of heat loss from changed wind velocity is accompanied by an alteration in the temperature of the surface, notwithstanding that the internal temperature be maintained.

The magnitude of the change in surface temperature will depend on the conductivity of the system and on the rate of heat loss. It will be greater with wet bodies than with dry, and any modification of the temperature of the evaporating surface will disturb the relation between heat loss and air movement. The observation of Hill *et al.* (1916) that above a wind speed of 25 m./sec. the rate of evaporation from the katathermometer ceased to increase, is an instance of such disturbance.

Constancy of surface temperature can, however, be sufficiently realized for dry bodies by utilizing a fine wire of high conductivity which is maintained at a uniform mean temperature, and for a wet surface by experimenting at wet-bulb temperature provided the air movement exceeds 150 cm./sec. The former method was exploited by King (1914); the latter we have used in the present investigation.

Even when due account is taken of surface temperature effects, the relation discovered between heat loss and wind velocity is strictly applicable only to the particular system investigated, for, according to Fishenden & Saunders (1930), who have made a comprehensive study of the data available concerning the heat lost from dry bodies by forced and natural convection, the power of the velocity according to which the heat lost by convection varies, is determined by the size and shape of the body. While no data are available for moist bodies, there is no reason to suppose that the relation between velocity and evaporation is not affected in some similar fashion by the size and shape of the evaporating surface.

Apparatus and methods

The system studied is a hollow copper cylinder filled with distilled water recently boiled *in vacuo* to remove CO_2. Its dimensions are 8 cm. long, 3·8 cm. in external diameter, with walls 1·6 mm. thick and a surface area of 120 sq. cm.

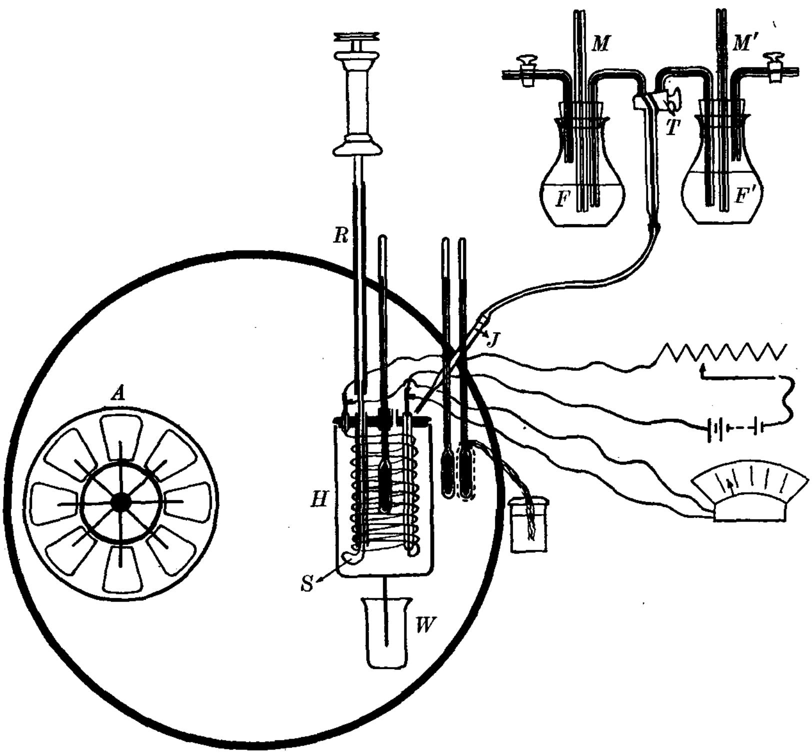

Fig. 1.

with its cotton jacket. Its general construction will be seen by reference to Fig. 1, *H*. From the centre of its lower surface projects a copper rod 1·5 mm. in diameter, and 46 mm. in length. This serves to collect the excess water from the moist covering and lead it to the collecting weigh-bottle (*W*).

The top of the cylinder is closed by a copper lid which is kept in place by two small countersunk brass screws and luted with bitumen. The lid is perforated by a series of openings. In the central opening is fixed the stem of a thermometer, the bulb of which is situated in the centre of the cylinder. The stem serves to suspend the cylinder from a clamp.

Two lateral openings give inlet to two glass tubes, each of which carries one of the leads to a heating coil. Another lateral opening serves for the passage of

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the stirrer (S), and, in a fifth, is inserted an open tube which serves for the filling of the cylinder. All the passages through the lid are made watertight.

The stirrer (S) is constructed of glass tubing, the lower end of which is sealed, flattened, and bent to form a single-bladed paddle. It passes through a glass tube of internal diameter just large enough to allow easy rotation. It is connected by means of a thick-walled rubber tube (R) to a rotating spindle above. The optimum rate of revolution for stirring was found to be 500 per min. The tendency to rotation of the liquid as a whole was diminished by the eccentric position of the stirrer and by two vertical baffles of celluloid (not shown in the diagram). These serve also to support the heating coil.

The water in the cylinder could be heated by passing a current through the spiral of Eureka wire. The wire was covered with a waterproof varnish. The spiral consisted of twelve whorls, 2·5 cm. in diameter. The upper and lower extremities of the coil were soldered to copper wires which passed through the lid of the cylinder. The resistance of the spiral and copper leads was 2·54 ohms.

The cylinder was covered with a tightly fitting jacket of cotton fabric. This was slipped on from above and tied below on to the projecting rod down which excess water was conducted into the weigh-bottle (W). The upper surface of the jacket was supplied with distilled water at any desired rate by the jet (J) from one or other of the flasks (F and F').

Each flask was furnished with a Mariotte's tube (M), so as to give a constant head of pressure. They were supported so that the ends of the Mariotte tubes were always in the same horizontal plane, but the height of their common plane could be varied at will.

From each flask a delivery tube led to a two-way tap (see Fig. 1, T), and from this tap a length of semi-rigid tubing carried the water to the feed jet. One of the flasks served for use between observations; the other was removed from its stopper and weighed before and after a determination. Each was provided with a third (air) inlet tube with a tap, so that when the feed outlet was closed the flask could be attached to its stopper without forcing water up the Mariotte tube.

Production of air currents

Some of the observations described in the first part, and all of those in Part II, of this paper, were made in wind currents issuing from a tunnel and possessing a rotational component. In the small wind tunnel available, it was much easier to observe and manipulate the pieces of apparatus at the mouth of the tunnel, and, by omitting baffles, a greater range of velocities was obtained.

Both these departures from standard method are open to criticism, and if we had had a larger and better wind tunnel at our disposal, inside which our apparatus could have been conveniently manipulated, we should certainly have used a linear flow for all our observations. However, as, with constant surface temperature, the same relation between change in evaporative loss and change in wind velocity was obtained whether we employed linear flow, measured by a Pitot tube, or a rather turbulent current of air with a rotational component, measured by a vane anemometer, the simpler method answered our purposes.

For these it was only essential to ascertain correctly the amount of change in ventilation around the cylinder from one experiment to another. The way we arrived at the apparent resultant velocity of wind currents impinging on the cylinder possessing a rotational component will be described in the next section.

The linear currents were produced by suction through a 3 m. tunnel of 25 cm. internal diameter. A fan, mounted on a triangular skeleton support and driven by a belt from an electric motor, rotated immediately within the aperture of the tunnel. The motor was shunt wound, and its speed was regulated by two rheostats, one in the field and one in the armature circuit. Two honeycomb baffles, the cells of which were 6 cm. long and 2 cm. square, were inserted, one immediately at the inlet and the other about 20 cm. from the fan. The tunnel was made of zinc lined with celluloid. For a distance of 40 cm. in the middle of the tunnel the metal covering was interrupted to allow the apparatus to be inspected. A trapdoor in the lower surface of the celluloid allowed the introduction and removal of a vessel for the collection of the small quantity of excess water from the cylinder. Holes in the celluloid allowed the thermometers, stirring tube, electric wires, and a Pitot tube to pass. All apertures in the celluloid were airtight. In this tunnel velocities up to 1500 cm./sec. were obtainable.

In those experiments in which no attempt was made to produce linear currents the fan was employed to create a pressure draft. It was placed 15 cm. from the mouth of the tunnel for reasons which will emerge later.

Measurement of wind velocity

The speed of the linear currents was measured with a National Physical Laboratory standard Pitot-static tube as described by Ower (1927). The muzzle of the Pitot tube was 1 cm. from the side of the moist cylinder, the latter being placed in the axis of the tunnel. The difference of pressure in the limbs of the Pitot tube was measured with a differential alcohol manometer mounted on the stage of a heavy microscope. The stage could be inclined at any angle, but 30° from the horizontal was usual. The excursions of the meniscus were measured by a micrometer eyepiece. By altering the magnification of the optical system the sensitivity could be varied at will.

As a measure of the velocity of the non-linear air current above 50 cm./sec. a 4 in. vane anemometer (A) was used. The anemometer was standardized by us against the National Physical Laboratory standard Pitot tube in a linear air current, and the corrections agreed with those supplied by the makers. It was mounted in a plane 9 cm. distant from and parallel to the outlet of the tunnel. The anemometer and cylinder were mounted so that their centre points were equidistant from the axis of the tunnel, and in the same equatorial

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plane. This was essential, as the wind speed at the axis was not the same as that at the periphery, and the air had some rotational velocity, the proportion of which varied slightly with the speed of linear current.

To simplify the calculation of the compounded velocity acting on the surface of the cylinder the obliquity of the rotational stream at the top and bottom of the cylinder was neglected and it was considered that there was a vertical component of the wind velocity. The value of this was measured with the anemometer, and a graph drawn giving the resultant velocity for each value of the horizontal component. In the tables of results of experiments in which a linear flow was not employed, "wind velocity" refers to the measure of forced convection arrived at in this way.

For the measurement of ventilation below 50 cm./sec. a hot-wire anemometer of the same length as the cylinder was used. The wire was of pure nickel, and its diameter 0·152 mm.

The hot-wire anemometer was employed to extend the range downwards, and was only employed in those experiments in which ventilation at higher speeds was measured by the vane anemometer. It was therefore calibrated by taking simultaneous readings with it and the vane anemometer under the experimental conditions in which both were used as a measure of wind velocity.

The readings of the vane anemometer were corrected for rotational component as described above, and the energy required to keep the wire at constant temperature plotted against the square root of these corrected readings. The points lay upon a straight line, and it was assumed that the extension of this line towards zero velocity could be used to calibrate the hot wire for velocities below those which the vane anemometer was capable of measuring. King (1915) concludes that the error of this extrapolation is less than 10%, even down to wind speeds of $\frac{1 \cdot 87 \times 10^{-2}}{d}$ cm./sec., where d is the diameter of the wire in cm., i.e. far below speeds for which we used it.

Measurement of atmospheric temperature and humidity

The dry- and wet-bulb temperatures of the air were determined by standardized thermometers which could be read to 0·1° C. They were placed 1·5 cm. apart and lateral to the cylinder. The pressure of water vapour in the air was calculated from the psychromatic formula $fa = fw - k(\theta_d - \theta_w)\frac{B}{755}$. The constant, k, varies with wind speeds below 300 cm./sec., so that, as small air currents were used in some of our experiments, it was necessary to determine the value of k for a number of speeds, plot them, and draw a smoother curve for use. The following values were found:

Forced convection

Cm./sec.	0	10	20	50	200	300
"k"	0·88	0·60	0·53	0·52	0·51	0·50

k was found to approach the asymptotic value of 0·5 more quickly than appears from the figures given by Skinner (1922).

Experimental procedure

A wind current of the desired velocity was drawn or driven through the tunnel by adjusting the revolutions of the fan. Water was fed from one of the flasks (*F*) to the jacket of the cylinder and time allowed for all conditions to become stabilized. Meantime the pressure head was adjusted so that the overflow was minimal. Constancy of overflow throughout an observation was essential. If, by chance, this was not attained, a correction had to be applied for differences in water retained in the jacket according to the rate of drip. The value of this correction was ascertained by plotting the weight of water retained in the fabric against the overflow in drops per minute. The other flask (*F'*), having been weighed with its contained water, was attached to its stopper, with the air inlet open, and the air inlet closed.

Preliminary to making an observation, and at the end, the wind velocity was measured either by the Pitot tube or anemometer.

An observation was started by putting the weighed flask (*F'*) into communication with the feed tube by a half-turn of the two-way tap (*T*) and placing a weighed bottle in position to collect the overflow. Simultaneously a stopwatch was released.

During the course of experiments in which heat was applied to the cylinder, the internal temperature was controlled by an observer who viewed the central thermometer through a telescope and adjusted the E.M.F. between the terminals of the heating coil by means of the rheostat (see Fig. 1).

The observation was terminated, after a sufficient interval, by another half-turn of the two-way cock, which changed the water feed back again to flask (*F*).

The water evaporated was ascertained from the loss of weight of the weighed flask less the weight of the overflow. From this the heat required for its evaporation was calculated by taking 585 cal. as the latent heat of evaporation. This value is midway between the highest and lowest surface temperatures obtaining in these experiments. The maximum error due to adopting this mean amounted to 1%.

From the E.M.F. required to maintain the interior of the cylinder at constant temperature the rate at which heat was supplied to the system was calculated. Neglecting, for the moment, radiant loss, which in these experiments was relatively small, the value of the heat exchange by conduction is obtained by the difference between total heat supplied to the apparatus and the heat lost by evaporation. A small allowance was made for the change of temperature of the water before evaporation and for any variation between the temperature of the water feed and the overflow.

The loss or gain of heat from the cylinder by means other than those directly measurable, such as loss from the structures passing through the lid, and gain by the conversion of the mechanical energy of rotation of the stirrer into heat energy, was found to play but a negligible part in the total heat exchange of the system.

Attempts to measure surface temperature directly

Following Aldrich (1928), we adopted a single thermocouple of fine constantan and copper wire 0·10 mm. diameter. The fineness of the thermocouple wires allowed them to be brought into regular and even contact with the surface of the cylinder by applying slight tension to the leads, and, as they covered a relatively minute area of the evaporating surface, the interference with evaporation was reduced to a minimum. About 1 in. of thin wire on either side of the constantan-copper junction was in contact with the cylinder. This allowed the junction to approximate to the average temperature of the surface. The thermocouple was calibrated by recording galvanometer deflexions with the hot and cold thermojunctions immersed in well-stirred water at different temperatures contained in thermos flasks. The deflexion amounted to 12·3 mm. for each 1° C. difference in temperature between the hot and cold junctions.

The surface temperature measured by a thermocouple of even the finest wire is not, however, the temperature of the evaporating layer because this layer is obliterated at the surface of contact. The layer, the temperature of which determines heat exchange by both evaporation and convection, is but of molecular dimensions and its temperature may be some degrees lower. It can, as we shall show in Part II, be derived from the rate of evaporation per unit area, when atmospheric conditions and wind current are known.

Attempts to ascertain the temperature of the evaporating surface with a sensitive radiometer were abandoned, owing to the small difference in temperature between it and that of surrounding objects.

EFFECT OF WIND ON EVAPORATIVE AND CONVECTIVE HEAT LOSS WITH CONSTANT SURFACE TEMPERATURE[1]

(1) *The function relating velocity of wind to heat loss by evaporation*

The effect of wind on evaporation was determined under the only condition in which surface temperature is both known and unaffected by changes in wind velocity. This is when the system is a gigantic wet-bulb thermometer. The cylinder was allowed to cool in wind currents of speeds from 150 to

[1] In the following sections the symbols used have the significance indicated below:

t_d = dry-bulb temperature ° C.
t_w = wet-bulb temperature ° C.
t_s = surface temperature ° C.
T_d = dry-bulb temperature (absolute scale).
T_s = surface temperature (absolute scale).
p_s = vapour pressure of water at evaporating surface.
p_a = vapour pressure of water in the atmosphere.
H_e = heat lost by evaporation (cal./sec.).
H_c = heat lost or gained by convection (cal./sec.).
H_r = heat lost or gained by radiation (cal./sec.).
H_t = total heat exchange (cal./sec.).

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1000 cm./sec. until its internal temperature was the same as that of the wet-bulb thermometer. The evaporating system is now in a state of dynamic equilibrium and the heat lost by evaporation is equal to the sum of the heats gained by convection and radiation. No flow of heat occurs within the cylinder, and the energy changes consequent upon variation in convection are independent of the internal conductivity of the system and are conditioned only by the form and extent of the evaporating surface and by the wind velocity.

Twenty-two measurements of the water evaporated in a recorded number of seconds, usually about 1 hr., were made. In eighteen of them linear currents were employed and the cylinder was placed in the middle of the wind tunnel; in four of them the wind had a rotational component and the cylinder was placed at the outlet of the tunnel. The apparatus and methods of experimenting are described in detail on pp. 62–63 above, in the section on Apparatus and Methods.

The observations were made in a large room in a centrally heated building. With few exceptions they were made during the evening when the atmospheric temperature and humidity remained sufficiently constant. The means between the temperatures of the dry bulb (t_d) and the wet bulb (t_w) at the beginning and end of an observation were used for calculation, but if either thermometer varied more than a few tenths of a degree the experiment was discontinued.

From the water evaporated per second, the evaporative heat loss, in calories per second (H_e), for each wind velocity was derived. As the atmospheric conditions were not always the same in the experiments with different wind velocities the slope of vapour pressure between the evaporating surface and that of the surrounding air ($p_s - p_a$) had to be allowed for before the effect due to wind current could be assessed. ($p_s - p_a$) in mm. of mercury was derived from the difference between the respective readings of the dry and wet bulb ($t_d - t_w$) by the usual psychrometric formula.

When the values obtained for $\frac{H_e}{(p_s - p_a)}$ were plotted against their respective wind velocities the points lay upon a curve, the form of which suggested a parabolic relationship and that evaporation $= CV^x$. By substituting the experimental values for $\frac{H_e}{(p_s - p_a)}$ and V, a number of values for x were obtained. Their mean was 0·65.

The heat lost by evaporation from this particular cylinder can therefore be expressed as $K_e\,(p_s - p_a)\,V^{0\cdot65}$, K_e being the evaporative constant of the system.

In Table I the observations are set out and also the values for $\frac{H_e \times 100}{(p_s - p_a)\,V^{0\cdot65}}$. The difference between the extreme values is 5%.

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Table I. *Linear currents*

t° C. dry bulb	t° C. wet bulb	$p_s - p_a$	V cm./sec.	g. H_2O evaporated	Time sec.	H_e cal./sec.	$\frac{H_e \times 10^2}{(p_s - p_a) V^{0.65}}$	H_r	H_c	$\frac{H_c \times 10^2}{(t_d - t_w) V^{0.7}}$
19·9	12·7	3·6	180	9·25	7950	0·648	0·62	0·11	0·538	0·19
18·6	13·0	2·8	200	2·00	1900	0·553	0·63	0·09	0·463	0·20
19·0	14·5	2·25	202	3·43	4290	0·437	0·61	0·07	0·367	0·20
20·5	13·1	3·7	235	7·51	5505	0·80	0·62	0·12	0·68	0·20
20·05	13·0	3·52	342	7·34	4595	0·97	0·62	0·11	0·86	0·21
18·7	14·2	2·25	342	4·99	4595	0·606	0·61	0·07	0·536	0·20
21·2	14·4	3·35	403	6·75	3690	1·00	0·60	0·11	0·89	0·20
17·4	10·9	3·25	412	5·88	3665	0·935	0·59	0·11	0·825	0·18
18·8	12·4	3·2	450	6·33	3597	1·03	0·59	0·10	0·93	0·20
20·45	12·9	3·78	587	8·88	3606	1·47	0·62	0·12	1·35	0·21
18·9	12·9	3·0	590	4·29	2120	1·18	0·60	0·10	1·08	0·21
18·6	13·5	2·55	630	5·40	3157	1·00	0·60	0·08	0·92	0·20
18·9	14·0	2·45	745	7·16	4003	1·352	0·60	0·08	0·955	0·19
19·0	12·2	3·4	790	10·16	3913	1·57	0·60	0·11	1·46	0·20
20·3	13·1	3·6	840	10·81	3720	1·70	0·59	0·11	1·59	0·20
19·8	11·8	4·0	871	12·55	3695	1·975	0·62	0·13	1·85	0·20
19·1	11·2	3·95	996	13·46	3664	2·14	0·60	0·13	2·01	0·20
19·7	11·4	4·15	1000	12·72	3383	2·28	0·60	0·13	2·07	0·20

Table II. *Wind currents with a rotational component*

Dry-bulb temp. ° C.	Wet-bulb temp. ° C.	$(p_s - p_a)$	V cm./sec.	H_e	$\frac{H_e + 100}{(p_s - p_a) V^{0.65}}$	H_r	H_c	$\frac{H_c + 100}{(t_d - t_w) V^{0.7}}$
14·1	7·7	3·2	152	0·65	0·78	0·10	0·55	0·26
14·0	7·7	3·15	312	1·05	0·79	0·10	0·95	0·27
14·2	7·8	3·2	418	1·24	0·77	0·10	1·14	0·26
14·0	7·6	3·2	552	1·50	0·77	0·10	1·40	0·26

(2) *The function relating velocity of wind to heat loss by convection*

If, from the heat lost by evaporation (H_e) at various wind velocities set forth in Table I, the gain of energy by radiation is subtracted, the convective gain of heat by the cylinder is obtained. From the Stefan-Boltzmann formula using $(8{\cdot}2) \times 10^{11}$ for value of σ in calories per minute the heat gained by the cylinder in calories per second by radiation (H_r) is

$$1{\cdot}38 \times 10^{12} \times A\ (T_s^4 - T_d^4) \times e,$$

where (H_r) is the radiant exchange expressed in calories per second, T_d and T_s[1] are the temperatures of the dry and wet bulb on the absolute scale, A is the area of the radiating surface, and e the emissivity. The cylinder had a surface of 120 sq. cm., and when wet an emissivity of 0·95.

The gain of heat by radiation has been calculated on the above basis and is set forth in column H_r of Table I, and the gain by convection in column H_c.

From the latter, the relation between heat gained by convection (H_c) and velocity of wind current can be arrived at in the same way as was used for evaporative heat loss by solving for x in the equation $H_c = K_c\ (t_c - t_s)\ V^x$. The value for x in this case was 0·7. The individual values for $\frac{H_e \times 10^2}{(t_d - t_s)\ V^{0.7}}$ (see right-hand column, Table I) are not so consistent as for $\frac{H_e \times 10^2}{(p_s - p_a)\ V^{0.65}}$, the extremes varying by 8%.

[1] It is assumed that surrounding objects were at the temperature of the air.

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Effect of wind on evaporative and convective heat loss when the surface temperature varies

The functions of V which apply when the surface temperature remains constant do not express the relationship of heat loss to wind velocity in the case of a moist body, the internal temperature of which is maintained above the temperature of the wet bulb. The influence of forced convection is less because the surface temperature progressively falls as the velocity of the wind increases.

Observations on the effect of wind upon the total heat lost

The internal temperature at the centre of the moist cylinder was maintained at approximately 16° C. above that of the surrounding air. The total loss of heat was ascertained by observing the E.M.F. which had to be applied to the heating coil to keep the central thermometer registering 35° C. The velocity of forced convection varied in the different experiments from 0 to 500 cm./sec. The observations are set out in Table III. At the same time the surface temperature was measured with the thermocouple described in the section on methods. From the surface temperature the magnitude of the radiant loss was calculated as before.

We were unable to make satisfactory determinations of the true radiation temperature with a radiometer, so had to use the temperature indicated by the copper-constantan couple as the radiating temperature. According to Aldrich (1928) this is not quite correct, but as radiation represented only a small fraction of the total heat loss, the adoption of the value derived from the thermocouple measurement introduces no serious error. The appropriate radiant loss (H_r) was subtracted from the total heat loss (H_t) at each velocity of air current. The sum of evaporative and convective loss (H_e+H_c) now varies much less with change in wind velocity than would be required by the expression $(H_e+H_c)=CV^{0 \cdot 7}$. The relationship is again parabolic, and at wind velocities of 89 cm./sec. and upwards is nearly proportional to $V^{0 \cdot 5}$.

Table III. *Evaporative and convective heat loss when the temperature of the surface falls as the velocity of wind increases*

Dry-bulb temp. ° C.	Wet-bulb temp. ° C.	Wind velocity cm./sec.	Total heat loss cal./sec. (H_t)	Thermo-couple temp. ° C.	Estimated radiant heat loss cal./sec. (H_r)	H_e+H_c cal./sec.	$\frac{H_e+H_c}{V^{0 \cdot 5}}$	$\frac{H_r}{H_t}$
19·0	(14·7)	(0)	1·60	34·5	0·28	1·32	—	0·175
18·9	14·0	16	2·38	33·9	0·27	2·11	0·528	0·114
18·7	13·9	38	2·84	33·8	0·26	2·58	0·420	0·094
18·6	13·9	89	3·95	33·1	0·25	3·70	0·392	0·063
18·4	13·7	150	5·10	32·3	0·25	4·85	0·394	0·049
18·5	13·9	322	7·35	31·5	0·23	7·12	0·396	0·031
18·4	14·0	425	8·41	30·3	0·21	8·20	0·396	0·025
18·7	14·1	505	9·24	—	(0·20)	9·04	0·400	0·022

Below a velocity of 90 cm./sec. the observed heat losses are greater than required by the square root relationship. This is due to the effect of the natural convection which then becomes comparable in magnitude to the forced convection. An estimate of natural convection in terms of forced convection when the surface temperature was 34·5° and the air temperature 19° C. (Exp. 1 in Table III, above) was made by substituting the observed loss of heat by evaporation and convection (H_e+H_c) in this experiment without forced convection in an equation empirically expressing the relationship between the sum of the heat lost by evaporation and convection when the velocity of the wind was 322 cm./sec. (Exp. 6 in Table III) in which $(H_e+H_c)=0{\cdot}396V^{0{\cdot}5}$. Substituting the observed (H_e+H_c) at zero forced convection we have $1{\cdot}32=0{\cdot}396V^{0{\cdot}5}$: hence, $V=11{\cdot}1$ cm./sec. This does not mean that the vertical stream of air over the surface of the warmed cylinder has this velocity. It merely indicates that its effect is equivalent to a forced convection of 11·1 cm./sec. The velocity of the upward streaming in natural convection is the same all round the cylinder, whereas that of the wind current is much greater at the sides, and at the centre of the back and front is, indeed, nil.

That an exponent of 0·5 best fits these observations, and all others we have made under similar conditions (see Tables III and IV), has no special significance. The extent of the variation of surface temperature with wind velocity depends on the internal conductivity of the system. When the cylinder was filled with kerosene instead of water the loss of heat varied more nearly with the cube root of the velocity.

The right-hand column of Table III shows the proportion of total heat loss represented by radiant loss. In still air 17·5% of the total loss occurs by radiation, but at a velocity of 150 cm./sec. only 4·9%, and at 505 cm./sec. only 2·2% occur by this means.

Relations between total and evaporative loss and wind velocity

The experimental procedure in this instance was similar to that employed when investigating the effect of wind velocity upon total heat except that during each observation the internal temperature was held constant long enough for a direct determination of evaporative loss in addition to total heat loss. The observations are set forth in Table IV. Low wind velocities were avoided because of the complicating effect of natural convection. Radiant heat loss has been neglected.

Table IV. *Total and evaporative heat loss when the temperature of the surface falls as the velocity of the wind increases*

Dry-bulb temp. °C.	Wet-bulb temp. °C.	Internal temp. °C.	P_a mm. Hg	V cm./sec.	H_t cal./sec.	H_e cal./sec.	$\frac{H_t}{V^{0{\cdot}5}}$	$\frac{H_e}{V^{0{\cdot}5}}$
19·0	13·9	30·0	9·2	68·5	2·51	2·09	0·304	0·254
19·0	14·0	30·0	9·5	129	3·53	3·16	0·310	0·278
19·0	14·1	30·0	9·7	274	5·08	4·30	0·307	0·260
18·6	14·1	30·0	9·9	571	7·54	6·45	0·316	0·270

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It will be seen from Table IV that not only total heat loss but also evaporative heat loss from the heated cylinder is nearly proportional to $V^{0.5}$.

Discussion

The recorded observations indicate that different relationships between heat loss and wind velocity may be deduced as the surface temperature is held constant or allowed to vary as the rate of heat loss alters. The magnitude of the difference is apparent from the chart (Fig. 2). The relationship deduced for the system investigated cannot be considered of universal application. Variations in size and shape will presumably alter the effect of wind on the

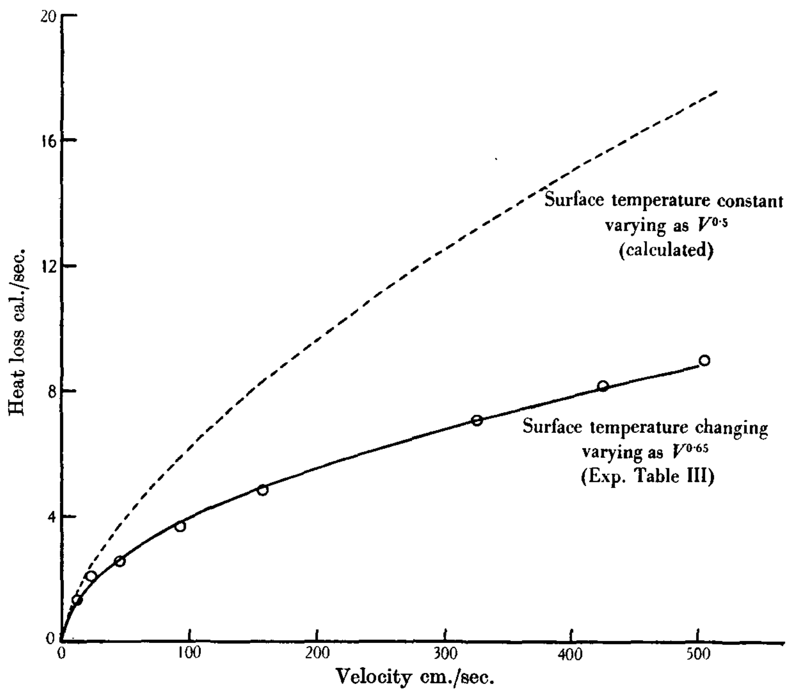

Fig. 2. Internal temperature, 35·0° C.; dry-bulb temperature, 18·4° C.; wet-bulb temperature, 14·0° C.

heat exchange when a constant surface temperature is maintained in much the same way as, according to Fishenden & Saunders (1930), they affect the relations between wind velocity and heat loss from dry bodies.

An additional disturbance is introduced by differences in internal conductivity in systems similar in size and form when the surface temperature is allowed to vary. Replacement of water in the cylinder employed by us with a liquid of lower conductivity, kerosene, reduced the exponent of the velocity in the expression relating it to total heat loss from 0·5 to 0·3, and if the stirring was inefficient the exponent was still lower. If in a single system the heat loss can vary either as the 0·65, 0·5 or 0·3 power of the wind velocity as heat transfer within the system is eliminated, is moderately efficient or poor respectively,

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the application of such relationships to systems of uncertain internal conductivity and unknown surface temperature is fraught with difficulties.

Loss of heat from the human body should, according to the data of Fishenden & Saunders (1930), vary with a power of the wind velocity considerably higher than the square root; possibly if the surface temperature were constant the loss would be closely proportional to the velocity. Owing to its capacity to lower its virtual conductivity by what amounts to inefficient stirring in a simple system, namely, by limiting the cutaneous circulation, the body can compensate for the disability inherent in its size, and in air currents of high velocity loses less heat than if no such change in its physical characteristics were possible.

Though the change from non-linear to linear air currents caused no alteration in the exponent of the velocity with which heat loss varied, both the evaporative loss and the convective gain in the experiments at wet-bulb temperature with linear currents were a constant fraction of the heat exchanges in non-linear currents of the same resultant velocity as measured by the anemometer. This we can only attribute to more complete ventilation of the surface of the cylinder by these non-linear and more turbulent currents.

The general relationship between heat loss and wind velocity must be such that when due allowance is made for natural convection it will hold at low velocities, and if extrapolated to give a value for heat loss in the absence of forced draughts must yield a result not widely divergent from the magnitude of the heat exchange possible by simple diffusion and radiation. Many observers have overlooked this and have deduced relationships from observations over a limited range of velocities which fail to agree with their own data at lower velocities and often suggest an incredibly large heat loss in still air. In view of the small heat exchange possible in the absence of convection currents when the temperature of the cooling body is low it has been neglected in this paper.

We were at first perplexed to find that convective and evaporative heat loss varied in a different manner with changes in the wind. Consideration of the behaviour of the wet-bulb thermometer in air currents suggests, however, that this must be the case. The wet-bulb temperature ceases to fall appreciably as soon as heat gained by convection and radiation and heat lost by evaporation approach equality with increasing wind velocities, and the minimum temperature is reached when radiation still represents about 10% of the gain by convection. If both evaporation and convective exchange varied as the same function of the velocity of air flow the temperature would only attain a minimum when the magnitude of radiation was negligible in comparison with the total heat exchange. As the velocity of the air rises above a certain threshold value the sum of the constant radiant and variable convective gain continually increases but is always equal to the evaporative loss which contains no constant component. This necessitates the conclusion that the functions relating evaporation and convective heat exchange to wind flow cannot be the same.

PART II

The effect of variations of atmospheric conditions on heat loss from a moist body

In the earlier part of this communication it has been shown how the loss of heat from the system described is influenced by changes in the wind velocity. The observed effects are usually the resultant of changes both in surface temperature and in the rate of air flow. In analysing the effects of changes in wet- and dry-bulb temperatures it will be possible to determine the magnitude of these surface temperature variations and to show that in a simple physical system the surface temperature may be derived from a preliminary calibration if the internal temperature of the system, the wind velocity and the atmospheric conditions are known. From these data the rate of heat loss from the system under any existing conditions can be predicted.

The effect of vapour-pressure changes on the rate of evaporation from liquid surfaces is generally expressed in terms of the difference between the pressure at the evaporating surface and the pressure of the same vapour in the surrounding atmosphere. There has been considerable variation in the complexity of the function of these variables chosen by different investigators.

Dalton (1802) appears to have been the first to attempt to determine the conditions governing the rate of evaporation. He suggested that evaporation is directly proportional to the vapour pressure of a liquid less the pressure of the same vapour in the atmosphere. This he confirmed by rough experiments. Stefan (1874) applied the laws he had formulated for the diffusion of gases to the phenomenon of evaporation which he regarded as equivalent to the diffusion of a gas. On theoretical grounds he developed the following formula

$$V=\frac{k}{h}\log\frac{B-F}{B-F_1}.$$

Here V is the volume of any vapour diffusing across unit area in unit time reduced to 0° C. and 760 mm., k is a constant, h is the distance of the evaporating surface from the opening of its containing vessel, B is the atmospheric pressure, F the pressure of the vapour in the air, and F_1 the pressure of the saturated vapour at the temperature of evaporation. Schierbeck (1895) has given an excellent review of the work on evaporation prior to the date of his paper. He introduces into Stefan's formula a further term to allow for the increase of density of the surrounding air with fall in the dry-bulb temperature. Schierbeck tested Stefan's formula experimentally by measuring the rate of evaporation of ether and water into still air from cylindrical vessels. The formula gave values approximating to those found experimentally, but Schierbeck's modified formula gave even closer agreement. Dalton's formula showed considerable divergence.

Schierbeck seems to have been the first to realize that the vapour pressure of the evaporating liquid can only be adequately determined if the temperature of the surface is known. This temperature he could not determine directly.

He states, however, that it must be between that of the body of the liquid and that of a wet-bulb thermometer moistened with the same liquid. For his experiments with ether, assuming the evaporating surface to be of the same temperature as the body of the liquid, gave the most consistent results. In the case of water, however, it was necessary to substitute the temperature of the wet-bulb thermometer. Schierbeck points out that whereas in still air his modification of Stefan's formula agreed with the experimental results, in moving air Dalton's original formula, modified to allow for changes in air temperature, gave better agreement. The pressure of the evaporating liquid is, in the case of water, measured by the wet-bulb temperature *in still air*. Schierbeck's experimental results certainly agree very well with both Stefan's and Dalton's formulae, but the range of difference in vapour pressure between the liquid and its surroundings was only small, and except with respect to wind velocity no great demands were made on either formula.

Hill *et al.* (1916), using the wet katathermometer in currents of air to measure evaporative loss, assumed that the vapour pressure of water at the surface of the bulb was the saturation pressure at the mean temperature of the cooling range. Assuming that the difference in the rate of heat loss from the dry and wet katathermometers was a measure of the rate of evaporation, they concluded that evaporative loss was proportional to the 4/3 power of the difference between the pressure attributed to the evaporating surface and the pressure of water vapour in the atmosphere.

The chief difficulty in the application of the vapour-pressure formulae is the determination of what is the temperature and therefore the vapour pressure of the evaporating layer. Schierbeck appreciated this and did his best to overcome it, but most of those who have treated the problem of heat loss from moist bodies have been constrained to make the assumption that the temperature of the surface is the same as that of the interior and have assumed that the temperature and, therefore, the vapour pressure at the surface, does not vary provided the internal temperature remains constant. In practice, however, no system is a perfect conductor, and the surface temperature is never that of the interior and departs from the latter value more and more as the rate of heat loss from the system increases.

A rational expression for the rate of heat loss from a moist surface of any size and shape will comprise terms involving convective, evaporative and radiant heat loss. If we make the assumption, as Dalton and Clark Maxwell did, that rate of evaporation is directly proportional to the difference in vapour pressures at the evaporating surface and in the surrounding atmosphere,[1] and if we accept the well-established relationships of convective and

[1] This is supported by Schierbeck's experiments over a limited range. It is probably because no one, so far as we know, except Schierbeck, has attempted to ascertain what is the true temperature of a surface evaporating in a current of wind, that has led some experimenters to doubt whether rate of evaporation is indeed a linear function of the difference between vapour pressure at the surface and that in the surrounding atmosphere. On p. 80 below we describe some experiments which afford direct experimental verification of Dalton's conclusion.

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radiant loss to temperature gradient, we may write the expression for total heat loss in the form

$$H = K_c (t_s - t_d) f(v) + K_e (P_s - P_a) f_1(v) + K_R (T_R^4 - T_d^4).$$

Here t_s is the temperature of the evaporating surface, t_d temperature of the dry bulb, T_R the absolute temperature at which radiation is occurring and T_d the absolute dry-bulb temperature. P_s is the maximum vapour pressure of water at the temperature of the evaporating surface, P_a the pressure of aqueous vapour in the atmosphere, and $f(v)$ and $f_1(v)$ are functions of the wind velocity. K_c, K_e and K_R are the convective, evaporative and radiation constants for the system under consideration and the particular units employed.

The constants K_e and K_c vary with size and shape; they also represent a number of physical constants involved in the transfer of heat and water vapour by diffusion as specified by Maxwell in the article on "Diffusion" in the *Encyclopaedia Britannica* (9th ed.), and also a term of the dimension of length converting difference of vapour pressure and difference of temperature into gradients. True gradients cannot appear as distinct terms in our equations, for there is no means of determining the distribution of vapour pressure and temperature around the system. In the system employed the values of all the unknown in the general expression for heat loss can be arrived at from the experimental observations. The temperature of the evaporating layer, t_s cannot be measured directly. Evaporation occurs from a film which is of only molecular dimensions, but it is the temperature of this boundary layer which determines both evaporative and convective heat exchange. It will be shown that the temperature of this surface layer can be estimated from the rate of evaporation.

Apparatus and methods

The apparatus was the same as that described in the first part of the communication. In addition to the manipulations previously described it was necessary to heat and moisten the air with which the cylinder was ventilated to obtain a satisfactory range of atmospheric conditions. The air currents in all the experiments described in this part possessed a considerable degree of turbulence and afforded more adequate mixing of the air than could have been achieved with the available apparatus if linear currents had been employed.

Control of atmospheric conditions

The experiments were performed in a centrally heated building, preferably on sunless days or after sundown. The windows were protected by inside and outside blinds, and the room temperature and atmospheric humidity could be varied considerably but could not be maintained constant over several hours. Accordingly, to produce and maintain different temperatures of the air entering the tunnel the air was warmed by electrically heated coils placed below the inlet of the tunnel, between it and the fan. The hygrometric state of the air was regulated by injecting dry steam into the entering air current. The variable resistances in series with the heating coils and the steam generator were enclosed in a well-ventilated fume chamber, and the steam pipe leading from the chamber to the tunnel was well insulated. Heating of the room from all these causes was thus minimized. The controls were conveniently situated outside the chamber and an observer was able to keep the dry- and wet-bulb temperatures at the outlet of the tunnel constant within 0·1° C. During the course of an experiment lasting several hours the atmosphere of the room became hotter and more saturated with water vapour. It was therefore necessary at the beginning of an experiment to regulate the wet- and dry-bulb temperatures of the air issuing from the tunnel so that they stood a few degrees above the readings of the corresponding instruments placed in the room at a distance from the apparatus.

Determination of evaporative and convective constants of the system employed

From any of the observations made upon the homunculus at wet-bulb temperature we could determine the value of K_e, for when the correct exponent of V had once been found as described in Part I, all the terms in the equation

$$H_e = K_e\,(P_s - P_a)\,V^{0 \cdot 65}$$

except K_e could be measured by experiment and from them K_e derived. It was not possible to obtain any considerable variations of $P_s - P_a$ at wet-bulb temperature, but Table V shows the values of K_e obtained over a wide range of velocities with moderate variation in the wet- and dry-bulb temperatures.

Table V

Dry bulb ° C.	Wet bulb ° C.	P_a mm. Hg	$(P_s - P_a)$ mm. Hg	mm. Hg	V cm./sec.	$V^{0 \cdot 65}$	H_e cal./sec.	$K_e \times 10^2$	$V^{0 \cdot 7}$	H_c cal./sec.	$K_c \times 10$
20·0	14·0	9·0	12·0	3·0	147	25·5	0·62	0·81	32·9	0·52	0·265
20·0	14·0	9·0	12·0	3·0	236	34·9	0·81	0·79	45·8	0·71	0·267
20·0	14·0	9·0	12·0	3·0	366	46·5	1·10	0·78	62·3	1·00	0·265
20·0	14·0	9·0	12·0	3·0	398	49·0	1·14	0·79	66·1	1·04	0·262
20·0	14·0	9·0	12·0	3·0	582	62·9	1·49	0·78	86·2	1·39	0·267
14·1	7·7	4·7	7·9	3·2	152	26·0	0·65	0·78	33·7	0·55	0·257
14·0	7·7	4·75	7·9	3·15	312	42·0	1·05	0·79	55·7	0·95	0·265
14·2	7·8	4·7	7·9	3·2	418	50·8	1·24	0·77	68·4	1·14	0·258
14·0	7·6	4·6	7·8	5·2	552	60·7	1·50	0·77	83·0	1·40	0·264

Mean value of $K_e = 0 \cdot 78 \times 10^{-2}$.

By substitution of the values of H_c, t_s, t_d and $V^{0 \cdot 7}$ from Table I in the equation $H_c = K_c\,(t_s - t_d)\,V^{0 \cdot 7}$, the values of K_c indicated in the final column of that table are obtained. The values $0 \cdot 78 \times 10^{-2}$ for K_e and $0 \cdot 26 \times 10^{-2}$ for K_c will be adopted.

Influence of varying internal temperatures on heat loss at constant wind velocity

The first observations in these experiments were made upon the homunculus at wet-bulb temperature. At a known wind velocity and with known atmospheric conditions the evaporative heat loss at wet-bulb temperature was determined. Total heat loss was in this case zero. Under similar conditions of environment and at the same wind velocity the internal temperature of the cylinder was raised, and at a number of points the total heat loss and evaporative heat loss were determined. Observations from three experiments are shown in Tables VI–VIII.

Table VI (Fig. 3)

Wet-bulb temp. 17·0° C. Dry-bulb temp. 21·0° C. Barometer, 768 mm. Atmospheric water vapour pressure, 12·5 mm. Hg (P_a). Wind velocity, 469 cm./sec. $V^{0·65}=54·7$.

Internal temperature ° C.	Total heat loss cm./sec.	Evaporative heat loss cal./sec.	$P_s - P_a$ mm. Hg	P_s mm. Hg	Calculated temperature of surface ° C.
17·0	0	0·79	2·0	14·5	—
22·2	1·99	2·16	5·45	17·95	20·3
23·65	2·60	2·62	6·6	19·1	21·4
25·7	3·52	3·23	8·10	20·6	22·7
29·8	5·15	4·46	11·3	23·75	25·0
33·6	7·09	5·83	14·7	27·2	27·3

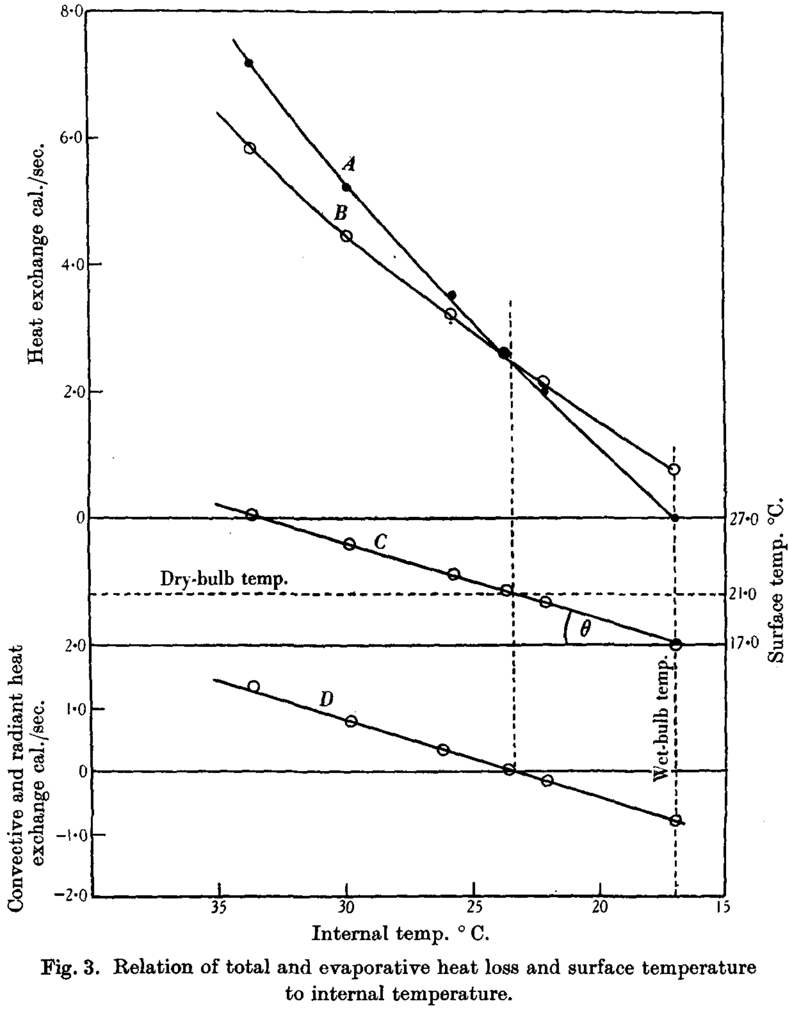

Fig. 3. Relation of total and evaporative heat loss and surface temperature to internal temperature.

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Table VII

Wet bulb temp. 17·1° C. Dry-bulb temp. 24·0° C. Barometer, 773 mm. Atmospheric water vapour pressure, 11·1 mm. (P_a). Wind velocity, 469 cm./sec. $V^{0·65}=54·7$.

Internal temperature ° C.	Total heat loss cal./sec.	Evaporative heat loss cal./sec.	$P_s - P_a$ mm. Hg	P_a mm. Hg	Calculated temperature of surface ° C.
17·0	0	1·42	3·5	14·6	—
23·9	2·63	3·20	7·85	18·95	21·2
27·7	4·18	4·31	10·6	21·7	23·4
30·8	5·45	5·22	12·9	24·0	25·15
35·7	8·15	7·29	18·0	29·1	28·4

Table VIII

Wet-bulb temp. 19·1° C. Dry-bulb temp. 29·0° C. Barometer 773 mm. Atmospheric water vapour pressure, 11·5 mm. (P_a). Wind velocity, 469 cm./sec. $V^{0·65}=54·7$.

Internal temperature ° C.	Total heat loss cal./sec.	Evaporative heat loss cal./sec.	$P_s - P_a$ mm. Hg	P_s mm. Hg	Calculated temperature of surface ° C.
19·1	0	2·09	5·1	16·6	19·1
26·5	3·20	4·31	10·5	22·0	23·75
32·75	6·09	6·56	16·0	27·5	27·45
35·95	7·85	7·84	19·1	30·6	29·3
38·7	9·62	9·14	22·3	33·8	31·0

The composite graph shown in Fig. 3 is constructed from the results of the experiment set forth in Table VI to illustrate the relationship between internal temperature and the following quantities:

(1) Total heat loss in unit time.

(2) Evaporative heat loss in unit time.

(3) Total heat loss less evaporative heat loss.

(4) Surface temperature.

The graph is divided into three sections. The uppermost pair of curves *A* and *B* represent total and evaporative heat loss as ordinate plotted against internal temperature as abscissa.

The middle curve (*C*) represents surface temperature, calculated from evaporative loss, as ordinate and internal temperature as abscissa. In the lowest section is a curve (*D*) showing the relation of the difference between total and evaporative heat losses, also plotted against internal temperature. A horizontal dotted line marks the level corresponding to dry-bulb temperature. As the experiments were carried out in an air current of 469 cm./sec., at which velocity radiant loss was small in comparison with either total or evaporative loss, it has been neglected. The smoothed curves drawn through the experimentally determined points intersect where total loss is equal to evaporative loss. At the point of intersection of the curves convective loss is nil and the surface temperature of the cylinder is equal to that of the surrounding air, and the vapour pressure of the surface the maximum vapour pressure of water at that temperature.

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Any vertical line drawn through the composite graph intersects the abscissa of each section at the same internal temperature. Consequently the points of intersection of such vertical lines with the curves represent simultaneous values of the variables illustrated in the graph.

A vertical dotted line is drawn through the point of intersection of the total and evaporative heat loss curves (*A* and *B*). It will be seen that it meets the lines of surface temperature at a point corresponding to dry-bulb temperature and the non-evaporative heat loss curve at the point corresponding to zero exchange. A second vertical dotted line denotes the wet bulb temperature. Graphs drawn from the data in Tables VII and VIII show the same general relationships, but the curves for total and evaporative loss intersect at different internal temperatures.

Here then is another method for the determination of K_e in the equation

$$H_e = K_e\,(P_s - P_a)\,V^{0 \cdot 65},$$

for P_a and V were known, H_e could be obtained from the graph, and P_s, as stated above, from the maximum vapour pressure at dry-bulb temperature.

The values of K_e obtained at constant wind velocity but under different environmental conditions by this latter method are illustrated in Table IX and compared with the values obtained from observations at wet-bulb temperature. The results are derived from the experiments summarized in Tables VI–VIII.

Table IX*

Dry-bulb temperature ° C.	Wet-bulb temperature ° C.	Internal temperature for zero conductive loss	V cm./sec.	Evaporative loss at point of zero conductive loss cal./sec.	Estimated value of K_e from heated cylinder	Value of K_e derived from measurement at wet-bulb temperature
21·0	17·0	23·5	469	2·50	0·74	0·71
24·0	17·0	28·5	469	4·50	0·73	0·74
29·0	19·1	35·3	469	7·55	0·75	0·74

* The jacket used in these experiments differed slightly from that with which the earlier values of K_e at wet-bulb temperature were determined. This accounts for the change of value of K_e from 0·78 to 0·74 in this series of observations.

We are justified, from these results, in applying to the heated cylinder the same general equation and the value of K_e derived from experiments on evaporative loss at wet-bulb temperature.

They also show that Dalton's conclusion that the rate of evaporation is proportional to the difference in vapour pressure between the evaporating surface and the atmosphere holds, for this is assumed in the calculation.

Application of the convective constant derived from experiments at constant surface temperature to experiments in which surface temperature varies

The values of K_c derived from wet-bulb observations may now be applied to the calculation of heat loss by convection from the data derived from the evaporative loss from the heated homunculus. The magnitude of the

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convective heat losses calculated may be compared with those observed as the difference between total heat loss and loss by evaporation.

From the series of experiments quoted in Table I we derived a mean value for K_c of $0{\cdot}26 \times 10^{-2}$. Applying this value in the formula

$$H_c = K_c\,(T_s - t_d)\,V^{0{\cdot}70}$$

we obtain the results shown in Table X.

Table X

Dry-bulb temperature (t_d) (° C.)	Calculated surface temperature (t_s) (° C.)	$(t_s - t_d)$ ° C.	$V^{0{\cdot}70}$	Calculated value of H_c cal./sec.	Observed value of H_c cal./sec.
21·0	20·3	−0·7	74·1	−0·14	−0·17
21·0	21·4	0·4	74·1	0·08	0·02
21·0	22·7	1·7	74·1	0·33	0·29
21·0	25·0	4·0	74·1	0·77	0·69
21·0	27·3	6·3	74·1	1·22	1·26
24·0	21·2	−2·8	74·1	−0·54	−0·57
24·0	23·4	−0·6	74·1	−0·12	−0·13
24·0	25·15	1·15	74·1	0·22	0·23
24·0	28·4	4·4	74·1	0·85	0·86
29·0	23·75	−5·25	74·1	−1·01	−1·11
29·0	27·45	−1·55	74·1	−0·30	−0·47
29·0	29·3	0·3	74·1	0·06	0·01
29·0	31·0	2·0	74·1	0·39	0·48

The observed values of H_c represent the difference of two numbers many times the magnitude of the difference. If this fact is borne in mind the agreement between the calculated and observed values of H_c is good.

METHODS BY MEANS OF WHICH THE TEMPERATURE OF THE EVAPORATING SURFACE MAY BE ASCERTAINED

As pointed out earlier, the temperature of the evaporating layer cannot be directly determined, but it can be arrived at in two ways.

A. *By measurement of the rate of evaporation*

We can apply the equation $H_e = K_e\,(P_s - P_a)\,V^{0{\cdot}65}$ to the determination of the temperature of the evaporating surface of the heated cylinder, by measurement of evaporative loss under known conditions of wind velocity and environment. For if H_e is measured the only unknown in the equation is P_s. We can obtain the value of this and from it the temperature of surface is found by reference to the vapour-pressure tables.

This method of analysis we have applied to the three experiments the results of which appear in Tables VI–VIII. The estimated surface temperatures are given in the last column of each of these tables, and those set out in Table VII are plotted as a function of internal temperature in Fig. 3.

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B. *By calculation when internal temperature, wet-bulb temperature and wind velocity are known*

From Fig. 3 it is clear that the surface temperature is a linear function of internal temperature and is related to this temperature and that of the wet bulb by the expression

$$\frac{t_s - t_w}{t_i - t_w} = C = \tan \theta,$$

where t_s is the temperature of the evaporating surface, t_i is internal and t_w wet-bulb temperature and C is a constant. C has the same value in spite of the change of atmospheric conditions in the three experiments and is equal to 0·62 if all the temperatures are expressed in degrees Centigrade.

The value of C varies with the wind velocity, but the nature and magnitude of this variation may be found by analysis of results already quoted. Evaporative loss actually varies very closely as $V^{0\cdot5}$ when the heated cylinder is exposed to air currents of different velocities, because the surface temperature drops as wind increases, but at constant surface temperature evaporative loss is found by the equation

$$H_e = 0{\cdot}78\ (P_s - P_a)\ V^{0\cdot65}.$$

By determining experimentally one value of evaporative loss at a known wind velocity we may obtain by substitution in the empirical equation

$$H_e = C V^{0\cdot5},$$

values of evaporative heat loss at any other velocity provided other conditions remain the same. Substituting these values in the equation

$$H_e = 0{\cdot}78\ (P_s - P_a)\ V^{0\cdot65},$$

we can derive the surface temperature from the vapour pressure (P_s) at each chosen velocity. With these data we can arrive at the value of C for each wind velocity by substitution in the equation

$$t_s = t_w + C\ (t_i + t_w).$$

The result of this procedure is shown in Table XI.

Table XI

Dry-bulb temp. 20·3° C. Wet-bulb temp. 18·9° C. Barometer, 770 mm. Hg. Internal temp. 38·0° C. Atmospheric water vapour pressure, 15·9 mm. Hg.

Wind velocity cm./sec. (V)	$V^{0\cdot65}$	H_e cal./sec.	P	Vapour pressure at surface (P_s) mm. Hg	Surface temperature (t_s) (° C.)	$\frac{t_s - t_w}{t_i - t_w} = C$
25	8·1	1·70	26·9	42·8	35·4	0·86
50	12·8	2·40	24·0	39·9	34·2	0·80
75	16·4	2·94	23·0	38·9	33·7	0·77
100	20·0	3·40	21·7	37·6	33·1	0·74
200	31·4	4·80	19·6	35·5	32·1	0·69
300	41·0	5·88	18·3	34·2	31·4	0·655
400	49·1	6·80	17·8	33·7	31·1	0·64
500	57·1	7·60	17·0	32·9	30·7	0·62

By drawing a smoothed curve to show this relationship between C and velocity it can be used to obtain the value of C from any intermediate value of V by interpolation.

The values of t_s obtained thus and also those arrived at from measurement of evaporative loss are set forth in Table XII.

Table XII

t_w ° C.	t_d ° C.	t_i ° C.	V cm./sec.	t_s by experiment ° C.	t_s calculated
18·8	20·2	38·1	222	32·5	32·0
16·2	29·3	40·2	211	31·6	32·5
15·1	26·5	36·5	528	27·6	28·4
12·5	17·2	18·2	270	15·8	16·3
10·1	16·0	39·5	229	29·3	29·3
9·8	15·8	30·0	500	22·2	22·4

It will be seen that in spite of a variation in wet-bulb temperature from 9·8 to 18·8° C., in dry-bulb temperature from 15·8 to 29·3° C., and in internal temperature from 18·2 to 40·2° C., the values of t_s obtained with the help of the curve (Fig. 3) are in substantial agreement with those obtained directly from each experiment. A further confirmation of the equation

$$t_s = t_w + C\ (t_i - t_w)$$

is afforded by the agreement between the predicted heat losses and those directly observed which we shall deal with under the next heading, for, in these predictions, the surface temperature was arrived at by means of it.

It would appear, therefore, that, in the case of our particular system, from a knowledge of its internal temperature and the wet-bulb temperature and wind velocity, the temperature of its evaporative surface and hence the rate of heat loss from it by evaporation and convection can be arrived at.

PREDICTION OF HEAT LOSS WHEN INTERNAL TEMPERATURES, WET- AND DRY-BULB TEMPERATURES AND WIND VELOCITY ARE KNOWN

The crucial test of the validity of our conclusions is the application of the derived formulae to the prediction of the rate of heat loss under various environmental conditions and a comparison of the predicted values with those determined experimentally. If wet- and dry-bulb temperature and the wind velocity are known the surface temperature of the homunculus can be found from the equation

$$t_s = t_w + C\ (t_i - t_w).$$

This value enables us to evaluate the vapour pressure at the surface, and since the vapour pressure of water in the atmosphere is known from the wet- and dry-bulb measurements, $(P_s - P_a)$ is obtained as the difference between these two pressures. The difference between surface temperature and dry-bulb temperature gives the value of the temperature gradient $(t_s - t_d)$ between the

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homunculus and its surroundings. All the terms on the right-hand sides of the equations

$$H_e = K_e (P_s - P_a) V^{0.65},$$

$$H_c = K_c (t_s - t_d) V^{0.70},$$

are then known and the magnitude of H_e and H_c can be determined.

The magnitude of the radiant exchange can be calculated from the surface temperature (t_R) measured by a suitable thermocouple

$$H_R = 1{\cdot}38 \times 10^{-12} (T_R^4 - T_d^4) \times A \times 0{\cdot}95,$$

where T_s and T_d are the absolute temperatures of the surface and the surroundings and A is the surface area of the homunculus in square centimetres and $1{\cdot}38 \times 10^{-12}$ is the radiation constant for a black body.

Examples of the measure of agreement between the observed and calculated values are shown in Table XIII.

Table XIII

Dry-bulb temperature ° C.	Wet-bulb temperature ° C.	Internal temperature ° C.	Wind velocity cm./sec.	$H_e + H_c$ calculated cal./sec.	$H_e + H_c$ observed cal./sec.
17·8	13·1	19·6	246	1·64	1·66
17·1	12·5	19·1	262	1·66	1·59
16·4	11·5	35·0	532	10·20	10·05
15·1	10·7	35·0	305	7·55	7·64
20·2	18·9	38·0	224	6·49	6·21
18·4	14·0	35·0	425	8·56	8·20

The effect on the rate of heat loss of change in temperature of the dry bulb when the temperature of the wet bulb, the wind velocity and the internal temperature remain constant

Haldane (1905), from observations upon human subjects, became convinced that the rate of heat loss from a sweating body was dependent upon the temperature of the wet bulb and little, if at all, influenced by variations in the temperature of the dry bulb. To test this, Martin (1923) mentions the results of five experiments made by him ten years earlier on the effect of varying the dry-bulb temperature on the rate of heat loss from a moist heated cylinder when the wet-bulb temperature was unaltered. The wind velocity varied from 1 to 3 m./sec. in the different experiments. A change in dry-bulb temperature of 6–8° C. varied the rate of heat loss ±2%, which is less than the error of these experiments. The apparatus and method of determining heat loss was similar to the one we have employed. The experiments of Rees (1927) with the wet katathermometer also indicate that heat loss is largely independent of the temperature of the dry-bulb thermometer.

We can ascertain to what extent heat loss from our moist cylinder is influenced by the temperature of the dry-bulb thermometer, for, having found (see Table XIII above) that its surface temperature at any given wind velocity depends only upon its internal temperature and the temperature of the wet bulb, the effect of changes in the temperature of the dry bulb can be calculated.

Suppose the dry bulb changes from t_1 to t_2 while the wet bulb remains the same, then, from the ordinary psychrometric formula relating vapour pressure to difference between dry and wet bulb the change in atmospheric water vapour pressure in mm. Hg is

$$0{\cdot}5\,(t_1 - t_2),$$

if t_1 and t_2 are expressed in degrees Centigrade.

Since surface temperature is unchanged the vapour pressure at the surface will not vary and the total change in vapour pressure gradient $(P_s - P_a)$ is $0{\cdot}5\,(t_1 - t_2)$.

The change in temperature gradient is $(t_1 - t_2)$.

Therefore the change in rate of heat loss is $K_e \times 0{\cdot}5\,(t_1 - t_2)\,V^{0{\cdot}65}$ cal./sec. and in convection heat loss is $K_c \times (t_1 - t_2)\,V^{0{\cdot}7}$ cal./sec.

Now a variation in dry-bulb temperature without any variation in wet-bulb temperature will affect convective and evaporative losses in opposite senses. The variations will to some extent compensate one another, and the total change of heat loss by evaporation and convection in unit time is

$$(t_1 - t_2)\,(0{\cdot}5K_e\,V^{0{\cdot}65} - K_c\,V^{0{\cdot}7})\text{ cal./sec.},$$

or giving numerical values to K_e and K_c

$$(t_1 - t_2)\,(0{\cdot}39\,V^{0{\cdot}65} - 0{\cdot}26\,V^{0{\cdot}7}) \times 10^{-2}\text{ cal/sec.}$$

There will be a further correction for the change in radiant loss due to fall in the temperature of surrounding objects. This is equal to $K_R\,(T_1^4 - T_2^4)$. This change will be in the same sense as that of convective exchange but will not be affected by the magnitude of the wind velocity, $K_R = 1{\cdot}58 \times 10^{-10}$, so that allowing for radiant exchange the total change in the rate of heat loss will be

$$(t_1 - t_2)\,(0{\cdot}39\,V^{0{\cdot}65} - 0{\cdot}26\,V^{0{\cdot}7}) \times 10^{-2} - 1{\cdot}58 \times 10^{-10}\,(T_1^4 \times T_2^4)\text{ cal./sec.}$$

Supposing, for instance, our cylinder were at an internal temperature of 35° C. in a wind current of 100 cm./sec. with a dry-bulb temperature at 37° C. and a wet-bulb temperature of 25° C., the rate of heat loss would be approximately 2·5 cal./sec.

If now the atmospheric conditions were modified so that the dry-bulb temperature fell to 27° C. while the wet-bulb remained the same, the change of rate of heat loss would be

$$10\,(0{\cdot}39 \times 20 - 0{\cdot}26 \times 25{\cdot}1) \times 10^{-2} - 1{\cdot}58 \times 10^{-10}\,(310^4 - 300^4) = 0{\cdot}13 - 0{\cdot}17 = -0{\cdot}04\text{ cal./sec.},$$

i.e. a fall in dry-bulb temperature of 10° C. increased the rate of heat loss but 1·6%. Similar examples may be chosen, and it will be found that even with variations of 20° C. in dry-bulb temperature, the rate of total heat loss is affected by only about 3%.

Haldane adhered to his conclusion formed in 1904 and maintained (1929) that for practical purposes it was only the wet-bulb temperature that mattered. To this there have been dissentients. Yaglou, Houghton & McConnell (cf. Yaglou, 1926, 1927) maintained that, even at high atmospheric temperatures, the dry-bulb temperature exerts a considerable influence. Yaglou (1927) and his colleagues found that when working at the rate of 29,000 kg.m./hr. in atmospheres of high temperature and humidity the increase in rectal temperature and pulse rate were better related to the effective temperature scale of Houghton & Yaglou (1923) than to the wet-bulb temperature. This scale is an ingenious contrivance which integrates the combined effects of the temperature of the dry and of the wet bulb and also air movement and expresses the result in terms of the temperature of still saturated air of equal comfort. Vernon & Warner (1932) and Bedford (1937) agree with Yaglou with some reservations.

In 1914 one of us (C. J. M.),[1] under the stimulus of Haldane, made experiments on himself to ascertain how far heat loss was independent of the air temperature when sweating profusely. The enquiry was interrupted by the War and never completed. Observations were carried out in an air-conditioned room in which the air movement was kept constant. Work was performed on a bicycle ergometer at the average rate of $\frac{1}{10}$ H.P. The experiments lasted 3 hr. The results of three experiments in which the wet-bulb temperature was 83° F. and the dry-bulb temperatures 86, 94 and 101° F. respectively, are illustrated in the accompanying chart (Fig. 4). Clad in soaked bathing

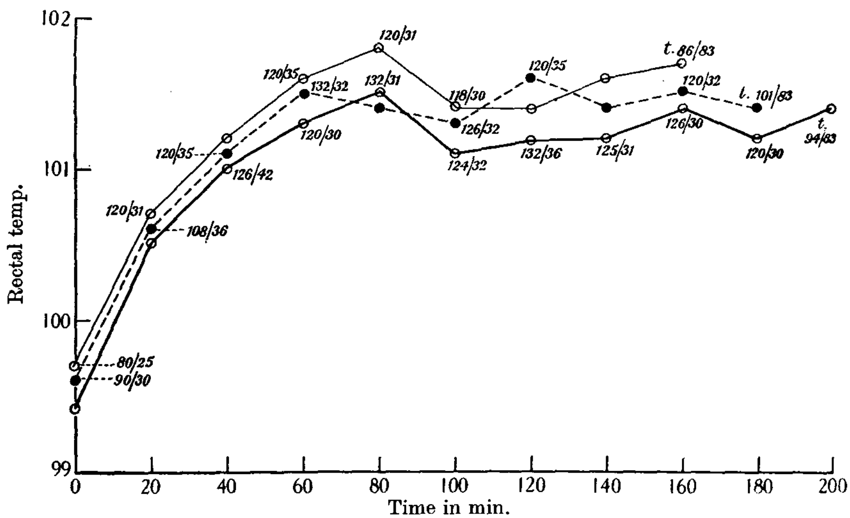

Fig. 4. Experiments (C. J. M.) Jan.–Feb. 1914, wt. 65 kg. Influence of work at high temperatures upon body temperature wet bulb 83°, dry bulb 86°, 94° and 101° F. Rate of work $=\frac{1}{10}$ H.P., 3300 ft. lb. = 456 kgm./min. Velocity of wind 210 ft./min. = 1·066 m./sec. = 2.38 m.p.h. The figures opposite each circle are pulse and respiration rate.

drawers only and sweating 1–2 lb./hr., neither the initial increase in body temperature, pulse and respiration nor the points at which these became stationary seemed to be influenced by 15° difference in the temperature of the air. On the other hand, when the temperature of the wet bulb was increased by 4° it was found impossible to carry on.

Vernon and Warner's (1932) more extensive experiments were also made upon themselves without clothes. They were, in many respects, similar to the above, but the work performed was only about half. They concluded that the disturbance of body temperature and heart and respiration rates corresponded more with the effective temperature of the surroundings than with the wet-bulb

[1] These experiments were alluded to by the author in his Croonian lectures to the Royal College of Physicians in 1930.

temperature. Agreement with the former was not so good in summer as in winter. This they attribute to "acclimatization". One factor in acclimatization is, we presume, more efficient sweating. They point out that some allowance for the dry-bulb temperature must be made unless the skin surface is covered all over with a layer of moisture and that this will not usually be the case.

There seems to us no doubt from the experience of so many observers in the United States and Great Britain that under usual conditions in hot surroundings heat loss from the human body is not entirely independent of the temperature of the dry bulb, and that either from insufficient sweating, covering some of the body with garments or radiation exchange it becomes operative.

Although exclusion of the influence of the temperature of the air on the rate of heat loss from a sweating body may be not quite correct in principle and its effect be by no means negligible in practice, the immense service rendered by Haldane to the mining community in riveting attention upon the supreme influence of the wet-bulb temperature must not be forgotten.

SUMMARY

It is emphasized that as heat exchange is controlled by the temperature of that boundary layer of molecular dimensions which separates a cooling body from its environment and from which evaporation occurs, attempts to relate heat loss with internal temperature have resulted only in empirical formulae. A rational formula involving the temperature of the evaporating surface is suggested, and it is shown how in the case of a system of sufficient simplicity all the terms can be either measured or derived from experiments.

The results of experiments with a small moistened cylinder are detailed illustrating the effect of wind velocity upon evaporative and convective heat loss under the one condition when the evaporating surface remains at constant temperature notwithstanding variations in wind, namely, when the whole system has been cooled to wet-bulb temperature. Evaporative loss is found to vary as $V^{0\cdot65}$, convective as $V^{0\cdot70}$.

Experiments are next described showing the effect of wind upon evaporative and convective losses when, the internal temperature being constant, the temperature of the evaporating surface fluctuates in consequence of varying wind velocity. Heat loss now varies very closely as $V^{0\cdot5}$ at velocities greater than 1 m./sec. At velocities below 1 m./sec. the same relation of heat loss to velocity obtains if due allowance be made for natural convection. This square root function is fortuitous, and heat loss varied between the square root and cube root of the velocity as the internal conductivity was diminished.

Attention is drawn to the impossibility of forming general conclusions from observations on any particular system, as the way in which the rate of

heat loss varies with the velocity of the wind depends not only upon the internal conductivity of the system but also on its size and shape.

Observations are described showing the influence of varying the internal temperature on total and evaporative heat loss with constant wind velocity and constant atmospheric conditions. These experiments furnish data from which the surface temperature can be derived from measurements of evaporation, and show that the temperature of the surface and the rate of loss of heat by convection are both linear functions of the internal temperature at any one wind velocity. They also show that the values of the constants of the system derived from experiments at the temperature of the wet bulb are applicable when the cylinder is heated.

An analysis of the results of the experiments with varying internal temperature indicates that the temperature of the evaporating surface (t_s) is related to the internal temperature (t^1) and that of the wet bulb (t_w) by the expression $\frac{t_s - t_w}{t_i - t_w} = C$. The value of C with varying wind velocity is ascertained by experiments, thus affording another means of arriving at the temperature of the evaporating layer. Values of t_s obtained in this way are compared with those determined by observing the rate of evaporation and show reasonable agreement.

It is shown how, knowing the temperature of the evaporating layer, the constants of the system employed and the effect of velocity of wind upon heat exchange, the rate of loss of heat by evaporation and by convection under given conditions can be predicted. Instances of the agreement between predicted and observed values are given.

From the formula representing the influence of atmospheric conditions on heat loss it can be shown, by calculation, that if the wet-bulb temperature remains constant considerable variations in the temperature of the dry-bulb influence but slightly the heat loss from the moist cylinder.

It will be seen that the analysis of the effects of environmental changes on the heat loss from a simple physical system such as was used presents no serious difficulties. Such an analysis, unfortunately, does not enable deductions to be made with reference to systems of different physical characteristics. How observations on such systems can be related in other than a qualitative manner to the effects of corresponding changes on living creature differing in size and shape and degree of moistening of their surfaces is not clear. When account is taken of the ability of living beings to alter the vascularity of their surface tissues and so to vary the temperature of the body surface while other factors remain constant, the difficulties in relating the cooling of any physical system to the loss of heat from animals become painfully apparent.

The most hopeful method of assessing the effect of air movement and atmospheric conditions on the heat loss from the human body seems to be in terms of a subjectively determined standard such as the effective temperature scale of Houghton & Yaglou.[1] The validity of such a scale has received support from observations by Houghton *et al.* (1924) and Vernon & Warner (1932) on the relation of pulse rate, body temperature, metabolism and other physiological variables to "effective temperature".

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[1] Similar methods designed by Missenard and himself are discussed by Bedford (1937).

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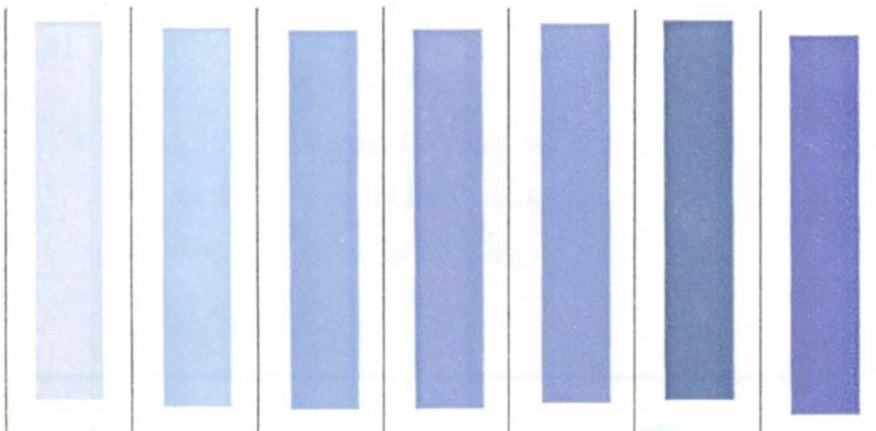

mg./litre	0·005	0·01	0·02	0·03	0·04	0·1	0·2
% by vol.	0·0004	0·0009	0·0017	0·0026	0·0035	0·0086	0·017

Fig. 6

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