THE INFLUENCE OF RADIANT HEAT AND AIR MOVEMENT ON THE COOLING OF THE KATA-THERMOMETER.

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(With 5 Figures in the Text.)

CONTENTS.

I. INTRODUCTION.

For several years past the kata-thermometer has been widely used in studies of heating and ventilation. The influence of radiation and convection on the rate of heat-loss from the instrument has been discussed in papers published by Sir Leonard Hill and his colleagues (Hill, Griffith and Flack, 1916, and Hill, Vernon and Hargood-Ash, 1922), but later work suggests that the relative influences of these two factors have not been estimated correctly. In view of the modern tendency towards heating buildings by radiation, it seems very desirable that the effects of radiation on the cooling of the kata-thermometer should be more accurately described, and it was with this object that the observations recorded in this paper were undertaken.

II. THE KATA-THERMOMETER IN STILL AIR.

A. THE BODY-TEMPERATURE KATA-THERMOMETER.

(1) *The kata factor.*

The cooling power (H) of the kata-thermometer is calculated from the equation

$$H = F/T \qquad \text{......(i)},$$

where T is the number of seconds taken in cooling through the range of 5° F., and F is the factor of the instrument. This factor is said to be equal to the total heat (in milli-calories) lost per sq. cm. in cooling through the range of 5° (Hargood-Ash and Hill, 1923). The time of cooling in a still air chamber is observed and the factor calculated from the empirical formula of O. W. Griffith (Hill, Griffith and Flack, 1916),

$$H = 0{\cdot}27\,\theta \qquad \text{......(ii)},$$

whence

$$F = 0{\cdot}27\,\theta T,$$

when $\theta = 36{\cdot}5$ minus the centigrade temperature of the air. Hill, Griffith and Flack found that the factor calculated in this way was practically constant over a range of from 4 to 33° C.

Angus (1924) found that the factor was constant at temperatures of 10–20° C., but showed a rather rapid rise at higher temperatures. He attributed the variability of the factor to the convection currents set up by the warm kata. By direct calorimetry and measurements of the bulb of the kata Angus also showed that the factor obtained by the still air chamber method does not give the true heat-loss, but under-estimates it by about 20 per cent. Hence, the values of H calculated from the factor obtained by the still air method do not give the true rate of heat-loss per unit area of the bulb.

Vernon (1926), covering a range of 10–30° C., found that the factor increased approximately in proportion to the temperature, but the values observed by him at the extreme temperatures investigated show some departure from the linear relationship in the direction indicated by our own results which are described below. Referring to Angus's results, Vernon says that the convection currents caused by the kata tend to become less and less rapid as the air temperature rises, and that for this reason one would expect the factor to show a gradual rise (such as he observed) and not a steady level below 20° C. followed by a rise. It is obvious that the convection currents set up by the kata decrease as the air temperature rises, but it does not appear to us to follow that the effect on the factor, as determined by the still air chamber method, is to cause the gradual increase observed by Vernon.

(*a*) *The kata factor as found in the still air chamber.*

For the further investigation of the influence of temperature on the kata factor, we have made careful determinations of the cooling times of different kata-thermometers in still air. For this purpose we used the water-jacketed air chamber described by Hill, Griffith and Flack; the chamber is a cube of 17 in. The inner surfaces were coated with a matt black paint. Throughout our observations the surface temperatures never differed from the air temperature in the chamber by more than a small fraction of a degree.

Observations were made on three katas, and the factors calculated for each temperature by means of equation (ii). For each instrument it was found that the factor varied inversely as $\theta^{0\cdot 06}$. Fig. 1 shows the results for the three katas. In order that the results for all three thermometers might be plotted on the same diagram the observed factors have been expressed as percentages of the value at 60° F.—the temperature at which Vernon suggested that the makers should calibrate the instruments. The curve is drawn from an equation of the form

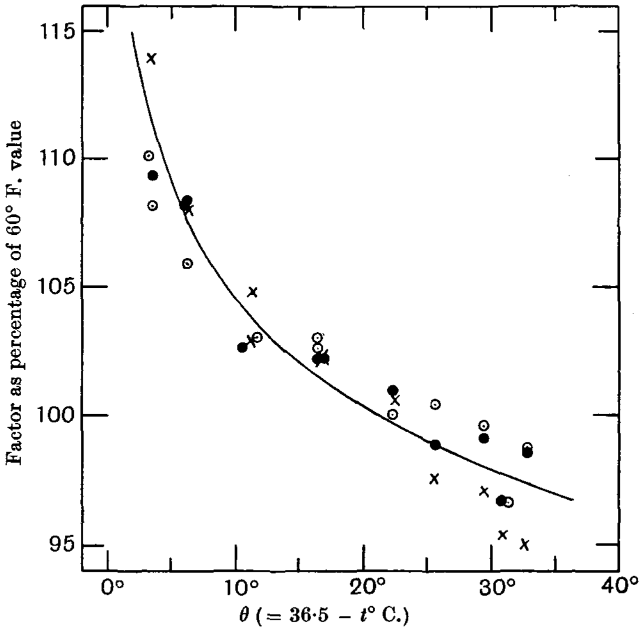

Fig. 1. Variation of kata factor (still air value) with temperature.

$$F = c/\theta^{0\cdot 06} \qquad \text{......(iii)},$$

c being a constant for each kata.

It is quite clear that the relation between kata factor and temperature is not linear.

(b) *The kata factor determined directly.*

It has been mentioned that Angus (1924) made direct calorimetric determinations of the heat given out by the kata in cooling through its range of 5° F. We have made similar measurements on various katas, by the same method, but instead of using mercury in the calorimeter, as Angus did, we used distilled water. Temperatures were measured by means of a thermocouple used in conjunction with a sensitive direct-reading galvanometer.

Table I shows the factors determined by the calorimetric method compared with those calculated from still air chamber observations.

Table I. *Kata factors as determined by calorimetric and still air methods.*

Kata-thermometer	Factor found by direct calorimetry	Factor found in still air at 60° F.	Percentage excess	Factor found by increasing still air value by 20 %
A	561	467	20·1	560
B	568	454	25·1	545
C	560	477	17·4	572

Mean excess = 20·9.

The factors found by direct calorimetry do not all show the same percentage excess above those arrived at by the still air method. In the calorimetry experiments the rise of temperature of the calorimeter and its contained water was only about 0·5° C., and a very slight error in determining this temperature rise causes a marked error in the final result. Although from 8 to 15 determinations were made for each kata, the results are still liable to a small percentage error. The data do, however, agree with those of Angus in showing that the true factor is about 20 per cent. higher than that found by the still air method at ordinary temperatures. More consistent results are obtainable by the still air method, and if for any reason the true factor of a kata is required we support Angus's suggestion that it should be taken as 20 per cent. greater than the value found in still air at 60° F. We have, in fact, used such a factor for calculations given in the next section of this paper.

As the factor ordinarily used is that determined by the still air method, it follows that the unit of cooling power is to some extent an artificial one, but if the factor is corrected to a standard temperature, *e.g.* 60° F., as suggested by Vernon (1926), the true rate of cooling will always be under-estimated by a constant percentage. In view of the large number of observations that have been made in past years it is not desirable to change the method of ascertaining the factor, but it is desirable that the factor should always be adjusted to a standard temperature, say 60° F.

(2) *Terminology.*

Hill has adopted the following symbols to represent the rate of cooling of the kata-thermometer,

H = total heat-loss,
H_R = heat-loss by radiation,
H_C = heat-loss by convection.

These symbols have always been used to denote the values calculated from the factor as determined by the still air method, so in this paper we shall continue to use these symbols for the same purpose. Where, as in the next section, reference is made to the *true* rate of heat-loss, the suffix T will be added to these symbols, thus H_T, H_{RT}, H_{CT} will represent total rate of heat-loss, and rates of heat-loss by radiation and convection respectively.

This terminology refers to the standard, or body-temperature kata, which cools from 100 to 95° F. In the paper reference will also be made to the high-temperature kata which cools from 130 to 125° F. To denote the heat-loss from this kata, as reckoned on the basis of the still air factor we shall use the symbols, H_1, H_{R_1}, and H_{C_1}, and for the true heat-loss from this instrument the symbols H_{T_1}, H_{RT_1}, and H_{CT_1} will be used.

(3) *Heat-loss by radiation and convection in still air.*

By Stefan's law the heat loss by radiation, H_{RT}, is given by

$$H_{RT} = E.\sigma\,(T_1^4 - T_0^4) \qquad \text{......(iv)},$$

where T_1 is the absolute temperature of the kata bulb, T_0 is the absolute temperature of the surroundings, E is a numerical constant depending on the emissivity, and σ is Stefan's constant.

Taking the value of σ as $1{\cdot}37 \times 10^{-9}$ (Fishenden and Saunders, 1932, p. 13), the rate of heat-loss can be expressed in milli-calories per sq. cm. per second by

$$H_{RT} = E\,.\,1{\cdot}37\,(T_1^4 - T_0^4)\,10^{-9} \qquad \text{......(v)}.$$

The emissivity of polished glass is given by Ten Bosch (Fishenden and Saunders, 1932, p. 21) as 0·90.

We have estimated the emissivity of the kata bulb by the use of a Moll radiation thermopile, and the mean value obtained was 95 per cent. of the emissivity of a matt black surface. Taking the emissivity of such a black surface as 0·95, that of the glass kata bulb is 0·90, which agrees with the value of Ten Bosch.

For the convection loss, O. W. Griffith deduced the equation

$$H_{CT} = 0{\cdot}0644\,(1 + 0{\cdot}002t)\,\theta^{5/4} \qquad \text{......(vi)},$$

where H_{CT} is expressed in milli-calories per sq. cm. per second, t is the temperature of the surrounding air in degrees C. In the derivation of equation (vi) it was necessary to make certain simplifying assumptions and the result could therefore only give an approximation.

In Table II are given the values of H_{CT} calculated from Griffith's equation,

Table II. *Rate of heat-loss from the body-temperature kata-thermometer in still air.*

	Rate of heat-loss at temperature (° C.) of								
	0°	5°	10°	15°	20°	25°	30°	33°	35°
H_{RT} (emissivity = 0·90)	4·46	3·95	3·41	2·83	2·23	1·59	0·92	0·50	0·22
H_{CT} (from equation (vi))	5·78	4·83	3·95	3·07	2·23	1·43	0·71	0·33	0·11
$H_{RT} + H_{CT}$	10·24	8·78	7·36	5·90	4·46	3·02	1·63	0·83	0·33
H (from equation (ii))	9·86	8·51	7·16	5·81	4·46	3·11	1·76	0·95	0·41
H_T (from equation (viii))	12·23	10·46	8·71	6·98	5·27	3·60	1·96	1·02	0·42
θ (= 36·5 − t° C.)	36·5°	31·5°	26·5°	21·5°	16·5°	11·5°	6·5°	3·5°	1·5°

and of H_{RT} for an emissivity of 0·90, for different temperatures. These values are calculated on the assumptions (*a*) that the temperatures of the air and the surrounding surfaces are the same, and (*b*) that the emissivity of these surfaces is 100 per cent. At ordinary temperatures the error involved by the latter assumption is probably very small. Taking the sum of H_{RT} and H_{CT} (calculated from this equation) we find that there is fairly close agreement with the values of the total rate of heat-loss (H) as given by the equation

$$H = 0{\cdot}27\,\theta.$$

Since this equation is based on cooling powers obtained by using the factor determined by the still air method, the value of H does not represent the true heat-loss. We found that the relation of the cooling time (T) to θ was given by an equation of the form

$$T = c\theta^{-1{\cdot}06} \qquad \text{......(vii).}$$

Taking the true factor as 20 per cent. greater than that obtained by the still air method at 60° F. the true rate of heat-loss H_T is represented by

$$H_T = 0{\cdot}27\,\theta^{1{\cdot}06} \qquad \text{......(viii).}$$

Values calculated from this equation are included in Table II. When these true values of H_T are compared with the sum of H_{RT} and H_{CT} it is clear that H_{CT} is considerably under-estimated by Griffith's equation (vi).

If from the true value of H_T as found by equation (viii) we subtract the value of H_{RT} given in Table II, we arrive at the true value of the convection loss (H_{CT}). Such values are shown in Table III. In his theoretical equation O. W. Griffith found that H_{CT} varied as the $\frac{5}{4}$ power of θ, but this was subject to a temperature correction based on the temperature coefficients of the various factors involved. E. Griffiths and A. H. Davis (1931), studying the convection losses from vertical cylinders of various heights, found that the average index of θ involved was about 1·25, but that this value varied with the height; the value was least with the shorter cylinders. The values of H_{CT} in Table III can be represented by the equation

Table III. *Rate of heat-loss, by convection, from body-temperature kata-thermometer in still air.*

	Rate of heat-loss at temperature (° C.) of								
	0°	5°	10°	15°	20°	25°	30°	33°	35°
H_{CT} ($=H_T - H_{RT}$)	7·77	6·51	5·30	4·15	3·04	2·01	1·04	0·52	0·20
H_{CT} (from equation (ix))	7·65	6·46	5·30	4·16	3·07	2·03	1·05	0·52	0·20

$$H_{CT} = 0{\cdot}1227\,\theta^{1{\cdot}149} \qquad \text{......(ix).}$$

Values calculated from this equation are shown in Table III, and they will be found to agree very well with the values obtained by subtracting the radiation loss (H_{RT}) from the total loss (H_T).

The total heat-loss (H_T) calculated from (*a*) equation (viii), and (*b*) by adding the radiation loss to the value of H_{CT} given by equation (ix), is given in Table IV. Fig. 2 shows the observed values of H_T, obtained by using three

Table IV. *Total heat-loss from body-temperature kata-thermometer in still air.*

	Rate of heat-loss at temperature (° C.) of								
	0°	5°	10°	15°	20°	25°	30°	33°	35°
H_T (from equation (viii))	12·23	10·46	8·71	6·98	5·27	3·60	1·96	1·02	0·42
H_T ($H_{RT}+H_{CT}$ from equation (ix))	12·11	10·41	8·71	6·99	5·30	3·62	1·97	1·02	0·41

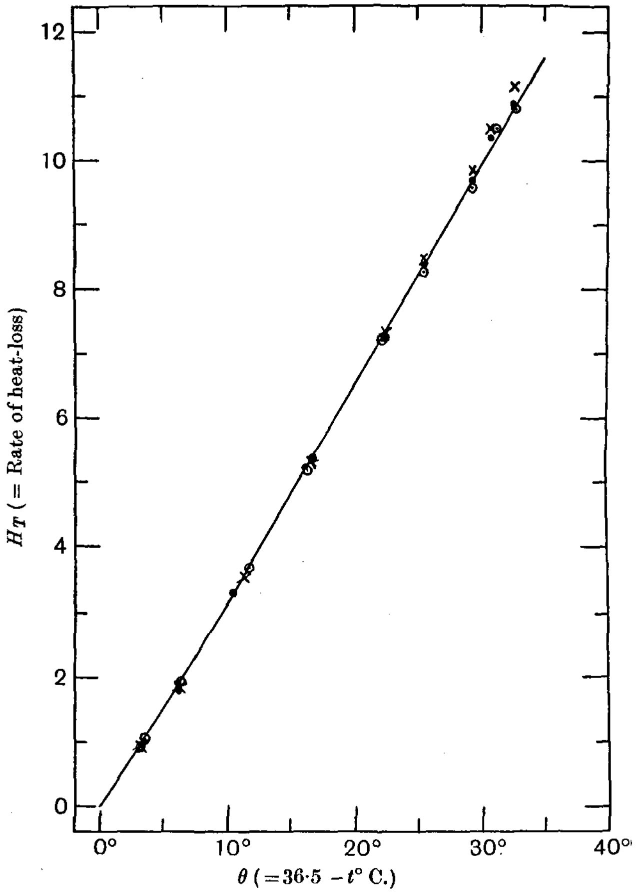

Fig. 2. Relation between air temperature and rate of heat-loss from body-temperature kata-thermometer in still air.

different katas, compared with the curve for $(H_{RT} + H_{CT})$; the agreement is very close.

(4) *Observations with a silvered kata-thermometer.*

Interesting confirmation of our equation for heat-loss by convection was obtained by using kata-thermometers with silvered bulbs. The bulbs were first coated with a film of silver by chemical deposition, and then a heavier coating was deposited by electrolysis. The thermometers were then burnished on a buffing wheel. The emissivity of the bulbs was estimated by means of the radiation thermopile, and the value obtained was 6 per cent. of black body emission. This value is high in comparison with values of 2 per cent. quoted by Fishenden and Saunders (1932), but our thermometers were imperfectly polished.

Observations of cooling in the still air chamber were made, and the rate of heat-loss calculated from the true factors as determined by calorimetry. For each of the two instruments used, the total heat-loss (H_{ST}) in still air can be expressed by

$$H_{ST} = 0{\cdot}13\,\theta^{1{\cdot}145} \qquad \text{......(x).}$$

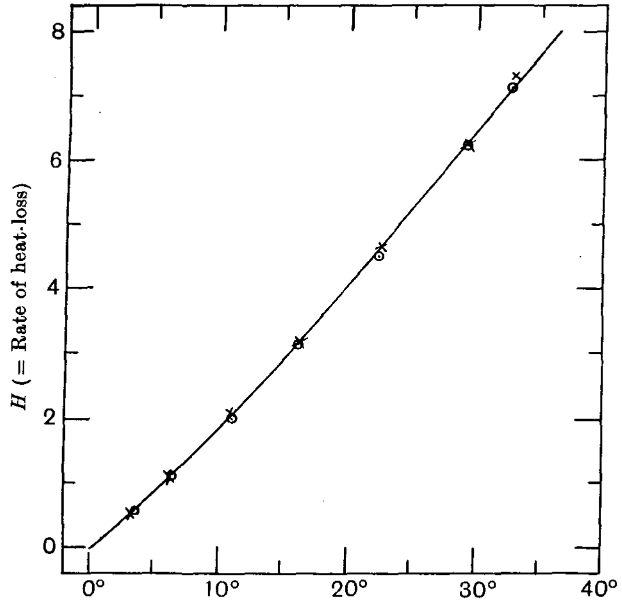

Fig. 3. Rate of heat-loss from silvered body-temperature kata-thermometer in still air.

In Fig. 3 the actual observations of heat-loss from these thermometers are plotted, and the curve is drawn from equation (x). The curve gives a very close fit to the observations. Values of H_{ST} calculated from this equation are given in the first line of Table V. In the next line are figures obtained by

Table V. *Rate of heat-loss from silvered body-temperature kata-thermometer in still air.*

	Rate of heat-loss at temperature (° C.) of								
	0°	5°	10°	15°	20°	25°	30°	33°	35°
H_{ST} (from equation (x))	7·99	6·75	5·54	4·36	3·22	2·13	1·11	0·55	0·21
H_{ST} (from H_{RT} (with emissivity of 0·06) + H_{CT})	7·95	6·72	5·53	4·36	3·22	2·14	1·11	0·55	0·21

adding together values of H_{CT} (from equation (ix)) and of H_{RT}, assuming an emissivity of 0·06. The two sets of values agree very closely, the maximum error being only a half of 1 per cent.

The factor of a silvered kata-thermometer can readily be determined by the application of equation (x). If observations are made in a still air chamber, we have, for the true factor

$$F = 0{\cdot}13\,\theta^{1{\cdot}145}\,T \qquad \text{......(xi)},$$

where T is the cooling time in seconds. To make readings of the silvered instrument comparable with those of the standard glass kata when the conventional still air value of the factor is used it is necessary that this value of the factor be reduced by one-sixth.

B. THE HIGH-TEMPERATURE KATA-THERMOMETER.

In addition to the observations on the body-temperature katas which have been described, further observations were made on some high-temperature katas cooling from 130 to 125° F. It was calculated from equations (v) and (ix), using the appropriate values of θ_1 and T_1, that the true factors of these katas should be 31 per cent. in excess of the values estimated by equation (ii) with the still air chamber at 60° F. This expectation was found to be justified when the factors estimated by calorimetry and by the still air method were compared, for with three thermometers the factors as estimated by calorimetry were respectively 30, 31 and 32 per cent. higher than the factors calculated from equation (ii) using still air at 60° F. We have therefore taken the true factors of these instruments as 31 per cent. higher than the still air values.

The rate of heat-loss in still air can be represented by the equation

$$H_{T_1} = 0{\cdot}306\,\theta_1^{1{\cdot}04} \qquad \text{......(xii)},$$

where $\theta_1 = 53{\cdot}0$ minus the centigrade temperature of the air. From Table VI

Table VI. *Rate of heat-loss from high-temperature kata-thermometer in still air.*

	Rate of heat-loss at temperature (° C.) of										
	5°	10°	15°	20°	25°	30°	35°	40°	45°	48°	50°
H_{RT_1}	6·56	6·02	5·44	4·84	4·20	3·53	2·83	2·09	1·32	0·84	0·51
H_{CT_1}	10·48	9·24	8·02	6·82	5·65	4·50	3·40	2·34	1·34	0·78	0·43
$H_{RT_1}+H_{CT_1}$	17·04	15·26	13·46	11·66	9·85	8·03	6·23	4·43	2·66	1·62	0·94
H_{T_1} (from equation (xii))	17·14	15·29	13·45	11·61	9·79	7·98	6·18	4·41	2·66	1·63	0·96
θ_1 ($=53-t$° C.)	48°	43°	38°	33°	28°	23°	18°	13°	8°	5°	3°

it will be seen that the values of H_{T_1} calculated from equation (xii) agree almost exactly with the sum of H_{RT_1} and H_{CT_1} calculated by using the appropriate values in equations (v) and (ix). This close agreement is also shown in Fig. 4, where the curve represents $(H_{RT_1} + H_{CT_1})$.

High-temperature katas were silvered and their factors determined by the calorimetric method. The emissivity of the silvered bulbs was estimated as described earlier, and a value of 0·05 was found. This value differs but slightly from the value of 0·06 found for the silvered body-temperature katas, and may be attributed to rather better polishing. However, the effect of such a difference on the total heat-loss is negligible. The equation to the heat-loss from these silvered katas was found to be

$$H_{ST_1} = 0{\cdot}138\,\theta_1^{1{\cdot}127} \qquad \ldots\ldots\text{(xiii)}.$$

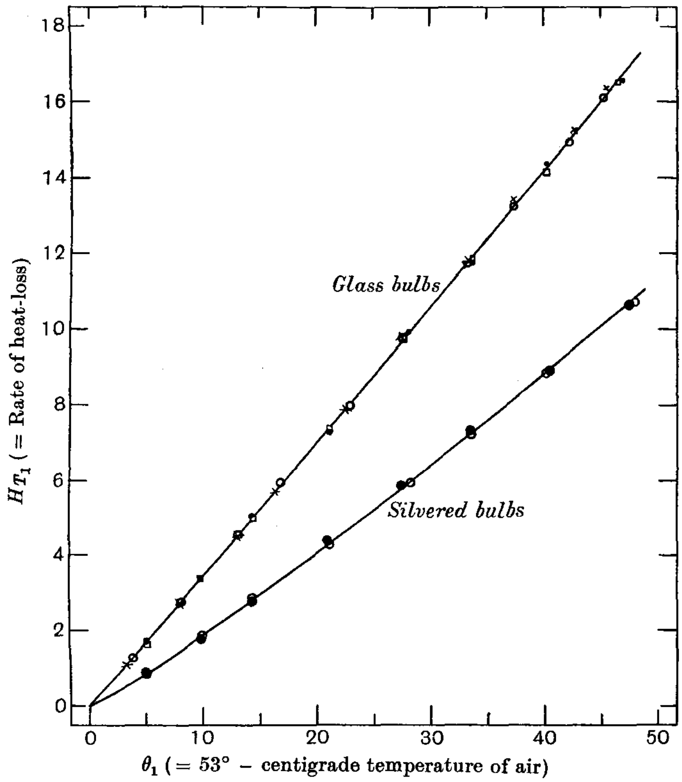

Fig. 4. Rate of heat-loss from high-temperature kata-thermometers in still air.

This equation gives very close agreement with the results obtained by calculating the radiation and convection losses separately from equations (v) and (ix), as will be seen from Fig. 4.

III. THE KATA-THERMOMETER IN MOVING AIR.

In considering the effects of air currents on the cooling of a hot body it is convenient to distinguish between "natural" convection and "forced" convection. In natural convection the air is still except for the currents set up by the heating effect of the hot body itself, while in forced convection the whole mass of the surrounding air is in motion. The influence of natural convection on the cooling of the kata-thermometer has been considered earlier, and in the present section the influence of forced convection is discussed.

(1) THE RELATION BETWEEN THE RATE OF HEAT-LOSS AND AIR VELOCITY.

Hill, Vernon and Hargood-Ash (1922) obtained empirical equations relating air velocity to temperature and rate of heat-loss from the body-temperature kata. These are

$$H = (0{\cdot}13 + 0{\cdot}47\sqrt{v})\,\theta \qquad \ldots\ldots\text{(xiv)}$$

for velocities of 1–17 m. per sec., and

$$H = (0{\cdot}20 + 0{\cdot}40\sqrt{v})\,\theta \qquad \ldots\ldots\text{(xv)}$$

for velocities below 1 m. per sec. It was not possible to fit a single equation of this type over the whole range of velocities. The observations with the higher velocities were made in a wind tunnel; those with the lower velocities were made by the whirling arm method, correction being made for swirl on the lines adopted by King (1914).

Other observers have obtained equations of the same type, and though their constants differ from those of Hill and Vernon, these equations all give substantially the same results with velocities of the order of 1 m. per sec. or more.

A more recent equation given by Angus, Hill and Soper (1930) is

$$H = \theta\sqrt{0{\cdot}29\,(0{\cdot}26 + v)} \qquad \ldots\ldots\text{(xvi).}$$

This formula covers a range of velocity of from 0·1 to 6 m. per sec., and is applicable to observations made with either the high-temperature or the body-temperature kata.

It should be noted that the values of H used in these equations are not the true values, but are calculated from kata factors determined by the still air method, and these factors should be adjusted to a standard temperature of 60° F. Such an adjustment we find can be applied by means of the equation

$$F = 0{\cdot}225\,T\theta^{1{\cdot}06} \qquad \ldots\ldots\text{(xvii)}$$

for the body-temperature kata, and

$$F = 0{\cdot}234\,T\theta_1^{1{\cdot}04} \qquad \ldots\ldots\text{(xviii)}$$

for the high-temperature kata, when T is the cooling time in seconds.

(2) THE INFLUENCE OF TEMPERATURE ON VELOCITY DETERMINATIONS.

Equations of the type of (xiv) and (xv) make no correction for any change in the influence of natural convection currents and radiation with variation of the air and surrounding surfaces. Vernon (1926) found that for a given low air velocity considerably lower values of H/θ were observed at 24° C.

than at 10° C., and this temperature effect diminished as the velocity increased. The greater part of this temperature effect was ascribed by Vernon to natural convection set up by the hot thermometer, but even at high velocities a small effect was noticed. No definite explanation of this latter effect was offered, though it was suggested that it might be due to differences in the humidity and density of the air.

Another temperature effect which was not referred to by Vernon is that the ratio of H_R (the heat-loss by radiation) to θ is not constant, but decreases as θ increases (*i.e.* as the temperature diminishes). The rate of heat-loss by radiation at different temperatures has already been shown in Table II. The figures given there represent the true heat-loss from this cause. It has already been shown that the values of H calculated from factors obtained by the still air method are one-sixth less than the true values; hence for the purpose of this discussion the true values of H_{RT} must be reduced to this extent. These adjusted values are given in Table VII, and in the same table are shown the values of H_R/θ. At 10° C. this ratio is 0·107, while at 30° C. it is 0·118. Thus the change in the ratio H_R/θ tends to counterbalance any temperature effect exerted by changes of density.

Table VII. *Radiation loss from body-temperature kata-thermometer, on basis of kata factor obtained by still air method.*

Temperature in ° C.	θ in ° C.	H_R	H_R/θ
0	36·5	3·72	0·102
5	31·5	3·29	0·104
10	26·5	2·84	0·107
15	21·5	2·36	0·110
20	16·5	1·86	0·113
25	11·5	1·32	0·115
30	6·5	0·77	0·118

Vernon recommended that a constant percentage correction should be applied to all values of H/θ of 0·60 or more. In later work, however, Hill, Angus and Newbold (1928) found that their observations (at velocities from 0·32 to 5·2 m. per sec.) did not, on the whole, show the same tendency. They conclude that for practical purposes and taking into account the size of the experimental error, a more complicated form of the equation of H/θ against $\sqrt{v}$ than a straight line is not necessary for the range covered.

At very low velocities, however, it would appear that some temperature correction might be necessary. In still air H/θ varies as $\theta^{0 \cdot 06}$, so that at 10° C. we have H/θ equal to 0·274, and at 30° C. it is 0·252. At such low velocities, therefore, it might be expected that a given air velocity would not correspond to the same value of H/θ over the whole temperature range. Vernon suggested that a percentage correction should be applied to the observed value of H/θ for every degree by which the temperature differs from 57° F., the temperature at which the low-velocity equation was determined. The corrections suggested decrease steadily from 0·44 per cent. per 1° F. when H/θ is 0·27 to 0·10 per cent. when H/θ is 0·60.

(3) THE PRESENT OBSERVATIONS.

(*a*) *On body-temperature kata-thermometers.*

(i) *On the standard kata-thermometer.*

For the purpose of checking the low velocity equation we made a series of observations using the whirling arm method. The correction for swirl amounted to 9 per cent., the same value as found by Hill, Vernon and Hargood-Ash. The temperature was from 20 to 21° C. in one set of observations, and 11° C. in another series, while the velocity ranged from 0·05 to 1 m. per sec. Six to eight observations were made at each velocity and the mean value used for calculating the equations. From Fig. 5 it is clear that H/θ bears a linear relation to $\sqrt{v}$, and the observation points are fitted by the line

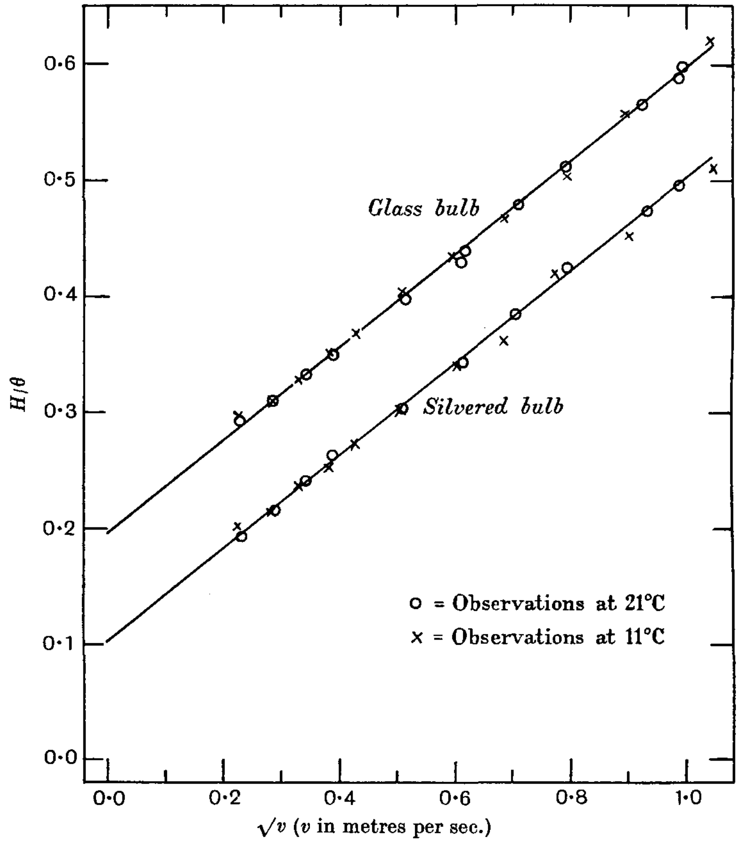

Fig. 5. Relation between H/θ and $\sqrt{v}$, for body-temperature kata-thermometers.

$$H/\theta = 0{\cdot}1955 + 0{\cdot}40\sqrt{v} \qquad \ldots\ldots(\text{xix}).$$

This is almost exactly the same as the equation derived by Hill, Vernon and Hargood-Ash (xii), the only difference being that their added constant is 0·20.

In the diagram (Fig. 5) different symbols are used to denote observations made at the different temperatures. It will be seen that the straight line drawn from equation (xix) fits both sets of observations equally well. We have tested the closeness of fit given by this equation by calculating velocities from the observed H/θ values, and comparing them with the actual velocities. The root-mean-square deviation of the expected from the actual values was 4·7 per cent. of the mean. When separate equations were calculated for the 11° and the 21° observations and a similar test made, the variability of expected from observed values was 4·3 per cent. It is clear, therefore, that over the range of temperature examined, there is no need to apply temperature corrections in calculating velocities, even when the velocity is as low as 0·05 m. per sec.

(ii) *On silvered kata-thermometers.*

The equations relating H/θ to air velocity are based on the assumption that the air and surrounding surfaces are at the same temperature. If the surface temperature differs from that of the air, the heat-loss by radiation, and therefore the total heat-loss, is altered, and any air velocity calculated from H/θ will be subject to error. As will be seen in a later section, if the observations are made near to any high temperature source of radiation this error will be pronounced. By using kata-thermometers silvered as described earlier in this paper it is possible very largely to overcome these errors. We have used the whirling arm method for calibrating these silvered instruments over the same range of velocity as was covered for the standard katas. The results are plotted in Fig. 5, and fit very closely to the line

$$\frac{H_S}{\theta} = 0{\cdot}101 + 0{\cdot}40\sqrt{v} \qquad \text{......(xx).}$$

On calculating velocities for the observed H_S/θ values the root-mean-square deviation of the expected from the observed values was found to be 5·7 per cent.

(*b*) *On high-temperature kata-thermometers.*

Similar observations have been made on high-temperature kata-thermometers with the bulb surfaces (*a*) of glass, and (*b*) silvered. It has been mentioned that Angus, Hill and Soper give one equation (equation (xvi)) as being applicable to either the high-temperature or the body-temperature kata. Their equation, like the other velocity equations that have been quoted, is based on cooling powers calculated from the usual still air factors. From our observations on the high temperature katas using velocities up to 1 m. per sec. we have obtained the following equations:

$$\frac{H_1}{\theta_1} = 0{\cdot}212 + 0{\cdot}351\sqrt{v} \qquad \text{......(xxi)}$$

for the ordinary glass bulb; and

$$\frac{H_{S_1}}{\theta_1} = 0{\cdot}109 + 0{\cdot}351\sqrt{v} \qquad \text{......(xxii)}$$

when the bulb is silvered. In equation (xxi) a velocity of 1 m. per sec. is indicated when $\frac{H_1}{\theta_1} = 0{\cdot}563$, but if the velocity were calculated from equation (xix) a value of only 0·844 m. per sec. would be obtained. It appears, therefore, that if the conventional cooling powers are used it is necessary to have separate equations for the high-temperature and body-temperature katas.

We have compared our data with values calculated from the equation of Angus, Hill and Soper (equation (xvi)). For the body-temperature kata, the root-mean-square deviation of expected from observed values was 5·5 per cent. of the mean, and for the high-temperature kata the deviation was 18·1 per cent.

(c) *A general equation for both types of instrument.*

In the equations which we have given connecting air velocity with the ratio H/θ, it will have been noticed that the coefficients of $\sqrt{v}$ vary. For the body-temperature kata the coefficient is 0·40, and for the high-temperature instrument it is 0·351. The reason for this difference lies in the fact that the equations are based on cooling powers obtained from kata factors estimated by the still air method. It has been shown that the true rate of heat loss from the body-temperature kata is 20 per cent. greater than the conventional value, and that the true loss from the high-temperature instrument is 31 per cent. greater. If the true heat-loss values are calculated the rate of heat-loss and air velocity can be related in one equation which is generally applicable to body-temperature or high-temperature katas, whether the bulb surfaces are of glass or are silvered. This equation is

$$\frac{H_{CT}}{\theta} = \frac{H_T - H_{RT}}{\theta} = 0{\cdot}123 + 0{\cdot}465\sqrt{v} \quad \ldots\ldots\text{(xxiii)}.$$

Using this equation, the root-mean-square deviation of 90 calculated velocities from the observed values was 9·1 per cent. of the mean observed value.

(4) THE EFFECT OF RADIANT HEAT ON VELOCITY DETERMINATIONS.

Reference has been made to the errors which may arise in the calculation of air velocities from kata observations if the thermometer is exposed to the radiation from a surface at a temperature differing markedly from that of the air. Some experiments were made to show the utility of the silvered kata-thermometer in avoiding such errors. A blackened copper bath with a vertical face 12 in. square was filled with boiling water, and the water maintained at boiling-point by a carefully screened gas flame. Observations were made with the bulb of the thermometer 10 in. distant from the middle of the vertical face of the bath, while the stream of air from an electric fan was directed over the bulb of the kata-thermometer in a direction parallel with the face of the bath. The air velocity calculated from the silvered kata-thermometer was 0·456 m. per sec., and it can be calculated that the error of this estimation was barely 4 per cent. Similar observations with the ordinary kata gave a calculated velocity of only 0·291 m. per sec., or 39 per cent. less than the true value. Further observations were made with the bulb of the thermometer only 7½ in. from the bath of boiling water, and it was found that the air velocity as calculated from the ordinary kata readings was under-estimated by 42 and 44 per cent., while the error in the values calculated from readings taken with silvered katas was only 3 or 4 per cent.

IV. THE MEASUREMENT OF RADIANT HEAT.

If a thermal environment is to be completely specified it is necessary that one should know the amount of radiation from the surrounding surfaces. Such information can readily be obtained by the use of a radiation thermopile. The thermopile is mounted on a suitable stand and observations are made with the instrument pointing in turn to all parts of the sphere surrounding the point of observation. The mean energy flux can then be expressed in terms of calories per square centimetre per second.

A thermopile sufficiently sensitive for such observations is a rather costly instrument, and the need for a galvanometer further increases the cost of the necessary apparatus. Apart from the question of cost, it is not always convenient to use the thermopile method of measuring the intensity of radiation, so as an alternative method we have tried to obtain an estimate by making parallel observations with kata-thermometers having bulbs (*a*) of glass, and (*b*) silvered. The energy flux was first estimated by the thermopile method already referred to, and then the kata observations were made. Three or four readings were made with each kata, readings being taken alternately on glass and silvered instruments. The air temperature was measured by a thermojunction, or by a mercury in glass thermometer with a silvered bulb. Finally, the radiation was again measured with the thermopile, and the mean of the initial and final thermopile estimations was used for comparison with the kata-thermometer estimate.

It has been said that the emissivity of the glass bulb is 0·9, and that of the silvered bulb 0·06; hence by subtracting the true rate of heat-loss of the silvered kata from that of the standard instrument $(H_T - H_{ST})$ we obtain a value representing the heat-loss by radiation from a kata with an emissivity of 0·84, since the convection loss is the same for both instruments. If this difference is multiplied by 0·90/0·84 one can ascertain the value of T_0 either from a table such as Table II, or by calculation from equation (v). T_0 is sometimes referred to by heating engineers as the "mean radiant temperature." The mean emission of radiation from the surroundings is then equal to

$$1{\cdot}37\,T_0^4 \times 10^{-9},$$

the flux being expressed in milli-calories (10^{-3} gram-calories) per sq. cm. per sec.

Observations were made in a room in which the conditions of heating and ventilation were varied. On some occasions the windows were widely open and on others they were shut, while at times there was no artificial heating and at other times the ceiling panels were turned on. Fourteen observations were made, and it will be seen from Table VIII that the estimates of the emission of radiation from the surroundings as made by (*a*) the thermopile, and (*b*) kata-thermometers, differ on the average by only 0·09 milli-calorie per sq. cm. per sec., or by less than 1 per cent. of the mean value. The corresponding "mean radiant temperatures" are shown in Table VIII. Taking the thermopile values as correct, the mean radiant temperature was estimated by the kata-thermometers with a mean error of 0·7° C.

Table VIII. *Emission of radiation from surroundings, as estimated by (a) radiation thermopile, and (b) kata-thermometers.*

Emission of radiation from surroundings (milli-calories per sq. cm. per sec.)			"Mean radiant temperature"		
Estimated by			Estimated by		
Thermopile ° C.	Kata-thermometers ° C.	Difference ° C.	Thermopile ° C.	Kata thermometers ° C.	Difference ° C.
10·13	10·25	0·12	20·3	21·1	0·8
10·06	10·36	0·29	19·7	21·8	2·1
10·05	9·93	0·12	19·6	18·8	0·8
10·00	9·92	0·08	19·3	18·7	0·6
10·07	10·17	0·10	19·8	20·6	0·8
10·22	10·35	0·13	20·9	21·8	0·9
10·27	10·24	0·03	21·2	21·0	0·2
10·26	10·24	0·02	21·2	21·0	0·2
9·89	9·87	0·02	18·5	18·3	0·2
9·96	9·87	0·09	19·0	18·3	0·7
9·96	10·06	0·10	19·0	19·7	0·7
9·98	9·95	0·03	19·1	18·9	0·2
10·15	10·10	0·05	20·4	20·1	0·3
10·22	10·35	0·13	20·9	21·9	1·0

Further observations were made in which the bulbs of the kata-thermometers were placed near a blackened copper bath containing boiling water, so that the solid angle subtended by the bath represented 7·7–11 per cent. of the sphere surrounding the bulb. On some occasions the current of air from an electric fan was directed towards the kata. The radiation from the surroundings other than the bath was estimated by thermopile measurements, and allowance was made for the emission from the bath in calculating the mean energy flux at the observation point. As in the observations already detailed, the estimates by thermopile and kata-thermometers differed by less than 1 per cent.

These observations are sufficient to show that the emission of radiant energy from the surroundings can be measured with reasonable accuracy by means of properly calibrated kata-thermometers.

V. SUMMARY.

The factor of the kata-thermometer as deduced from the relation

$$F = 0{\cdot}27\,\theta \times \text{cooling time in seconds}$$

is not constant, but increases as θ decreases. The relation between F and θ

is shown, and it is recommended that the factor should always be corrected to the value corresponding to a temperature of 60° F.

The rate of heat-loss calculated from the factor determined by the still air method is not the true value, but under-estimates it. If the true value is required it can be obtained with reasonable accuracy by increasing the still air value of the factor by 20 per cent. in the case of the body-temperature kata, and 31 per cent. in the case of the high-temperature instrument. For ordinary use however, it is recommended that the still air factor should continue to be used.

Observations were made in still air with standard kata-thermometers and also with silvered instruments. From these observations, and from determinations of the emissivity of the bulbs, the heat loss by radiation was estimated. The remainder after deducting the radiation loss from the total heat loss gave the loss by convection. Estimations of the convection loss from the silvered and plain katas corresponded closely. An equation is given for the convection loss in still air.

The whirling arm method was used for investigating the effects of air velocities up to 1 m. per sec., corrections being made for swirl. The equation deduced from these observations on the standard body-temperature katas was practically identical with the equation of Hill, Vernon and Hargood-Ash. An equation of similar form was found for the silvered body-temperature kata-thermometers, and equations are also given for the high-temperature instruments. When the true rate of heat-loss is used it is found that one equation can be made to fit the observations with both high-temperature and body-temperature instruments, whether the bulb surfaces are of glass or silver.

It is shown that in places where the temperature of the surrounding surfaces differs from the air temperature, a much more reliable estimate of the air velocity can be obtained if a silvered kata is used instead of the plain glass instrument.

A method is given for measuring the emission of radiation from the surroundings by means of ordinary and silvered kata-thermometers, and it is shown that estimates so made correspond, to within 1 per cent., with the values obtained by direct thermopile measurements.

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