On the Cooling and Evaporative Powers of the Atmosphere, as Determined by the Kata-thermometer.

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Part I.—*Cooling Power in Moving Air. The Kata-thermometer as an Anemometer.*

In a paper published in 'Phil. Trans.' (B, vol. 207, 1916, pp. 183–220) by L. Hill, O. W. Griffiths, and M. Flack, there was detailed the theory and use of an instrument, the kata-thermometer, a large-bulbed alcohol thermometer, for determining the cooling power of the atmosphere on a surface at body temperature. A formula $H/\theta = 0{\cdot}27 + 0{\cdot}36\sqrt{V}$, where H = heat lost in mille-calories per square centimetre per second, $\theta = (36{\cdot}5 - t)^\circ$ C., where t = temperature of enclosure, and V = velocity of air current in metres per second, was obtained for the loss of heat of the dry kata-thermometer in a current of air; 36·5° C. was chosen as the skin temperature. This is a variable, and only reaches that figure in warm atmospheres.

The constant 0·36 in the above formula was determined from experiments which were carried out with the apparatus then available in a tube of which the cross-section area was of the same order of magnitude as that of the kata. Therefore, in calculating the velocity of the air current, *i.e.*, the mean velocity of the air striking the kata, the area of cross-section of the kata was subtracted from that of the tube.

In later experiments the authorities of the East London College have been good enough to allow us the use of the large wind tunnel and other smaller tunnels established for aeroplane observations. Mr. N. A. V. Piercy, the lecturer on Aeronautical Engineering, has kindly helped us to determine very exactly the velocity of the wind in the tunnels.

In all three tunnels used the air was drawn through the tunnel by means of a large electric fan, and the velocity deduced from the difference of pressure inside and outside the tunnel, the gauges used being calibrated by means of a Pitot tube. All the tunnels were of square cross-section. The largest tunnel used was 48 inches wide and made of steel. The pressure difference was read from tilted gauges, the velocity being given by the formula :—

$$V = K\sqrt{d},$$

where V is the velocity in metres per second, K a constant depending upon

the gauge and tunnel and determined by comparison with a Pitot tube, and d the difference of level of the liquid in the two arms of the gauge.

In all the observations taken the kata was heated in hot water in a Thermos flask, being kept in the water till the air space at the top was about half full of alcohol. The same kata, stop-watch, and thermometer, the last graduated to 0·1° C., were used throughout the experiments. In the Royal Society paper cited above it is detailed how a factor is determined for each kata by which the readings can be expressed as cooling powers in mille-calories per square centimetre per second.

The value for the kata factor was re-determined before being used in an enclosure of still air jacketed with water, the results obtained being as follows :—

Mean time of cooling = 105·9 seconds.
Temperature of enclosure = 17·8° C.
$\theta = 36{\cdot}5^\circ - 17{\cdot}8^\circ = 18{\cdot}7^\circ$ C.

The factor $= 0{\cdot}27\theta \times$ mean time of cooling (105·9) = 535. The graph obtained from the result of these later experiments and plotted in a similar manner to that obtained from the earlier ones, gives the value of the constant a in the formula $H/\theta = 0{\cdot}27 + a\sqrt{V}$ as 0·49. The figures obtained are given in Table 2.

The difference in the value of the constant found from the two sets of experiments suggested that the true mean velocity had not been obtained in the earlier work, and on re-considering the problem it appeared probable that if half the area of cross-section of the kata in place of the whole were subtracted from the sectional area of the tube used in the earlier work a more correct value of the velocity would be given. Calculating the velocity in this way the value of the constant becomes $0{\cdot}36 \times 1{\cdot}32 = 0{\cdot}48$, which is in close agreement with the value obtained from the later experiments.

We tested the new constant by using it in measuring the velocity of the wind with the kata against the standard anemometers at Kew Observatory, and we are much indebted to Dr. Chree for the facilities he gave us to do this.

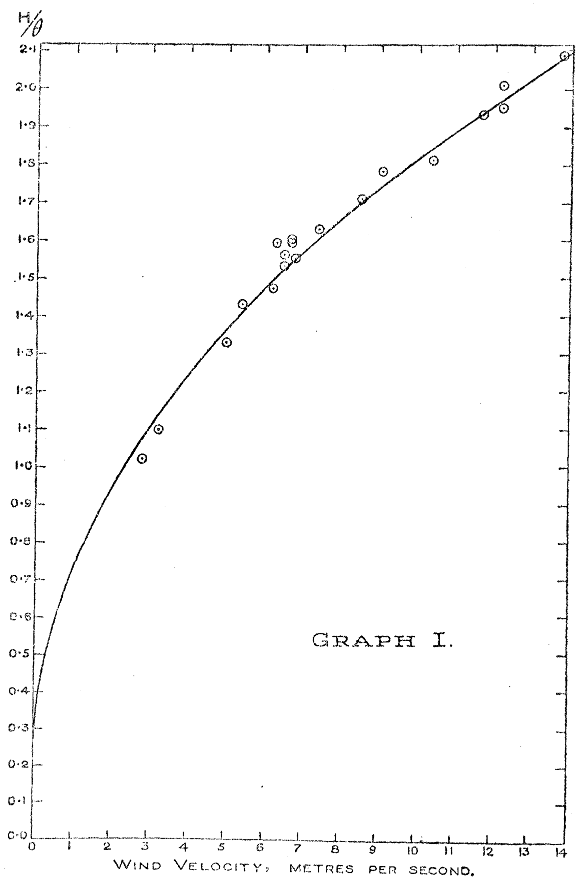
A succession of kata readings were taken during each period of time and the mean of these taken, while the anemometer records were continuous. An extra strong gust may thus be missed by the kata, if no reading happened to be taken at that moment. This possibly was the case in the third series of observations given in Table 1.

Table 1 shows the values obtained for wind velocities by a Robinson's cup anemometer, a Dines pressure tube, and a kata-thermometer. The

observations were taken on the roof of Kew Observatory. The day was one with a steady strong breeze :—

Table 1.

Time.	Wind velocities (metres per sec.).		
G.M.T.	Cup anemometer.	Pressure tube.	Kata.
x 40 – x 50	6·0	6·5	6·4
x 55 – xi 5	6·5	6·25	6·6
xi 10 – xi 20	6·0	5·1	5·2
xi 20 – xi 30	6·4	5·7	6·3

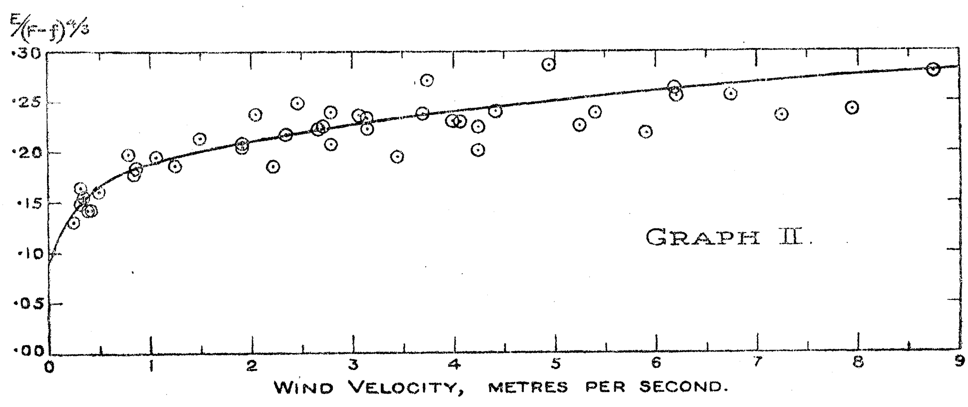


The cup anemometer is regarded as the more accurate instrument. The agreement with the readings of the cup anemometer is close enough to establish the claim that the kata-thermometer is an accurate anemometer.

It must be borne in mind that the kata must be shaded from the sun's rays, direct or reflected, when used as an anemometer. The kata shows the effect of eddies and air movements which are too small to affect cup or fan anemometers. This gives it an especial value in the investigation of the ventilation of rooms.

As shown in the paper cited above, there is a limiting velocity value beyond which the kata no longer follows the formula.

With respect to the observations detailed in Table 2, a certain amount of variation was found in the values obtained for the constant, the mean value as given by the graph being 0·49. This variation may be due to (*a*) experimental errors of observation, (*b*) errors due to causes the effect of which could not be determined. In this latter class would be included errors due to the fact that the kata, being a very sensitive instrument, detects a slight change in temperature or velocity before it is shown by thermometer or pressure gauge. Errors due to radiant heat, alteration of pressure, or to changes in the glass and liquid of the instrument must also be included in class (*b*). For example, it was found that the temperature of the water in which the kata was heated had a slight effect on the cooling power, this being greater when the water was at a temperature of 80° C. than when it was 45° C. Water in a Thermos flask at about 80° C. should be used for all kata observations.



GRAPH II.

In this connection it may be noted that the first of a series of observations of cooling of the kata is not reliable and should be neglected. Since errors under class (*a*) would be eliminated by taking the mean of a number of observations (as was done), it would appear that the variation in the constant must be due to undetermined causes. This is also pointed to by the fact that observations taken on any one day gave constant values.

If the kata is used to determine the cooling power under ordinary conditions of wind and temperature, the loss of heat is obtained by dividing the kata factor by the time of cooling, hence the formula $H/\theta = 0{\cdot}27 + 0{\cdot}49\sqrt{V}$ does not enter into the calculation. To deduce the wind velocity from the cooling power, however, the above formula is used, and an error not exceeding ± 12 per cent. may occur in the result, this error being due to the variation of the constant discussed above. For example, if the velocity given by the kata is 2·5 metres per second, then the true velocity will lie between 2·2 and 2·8 metres per second. Similarly, in calculating kata cooling powers from temperature and wind velocity data published in the meteorological reports, errors of the same magnitude may come in.

Table 2.—Values Obtained from Experiments in Wind Tunnels.

H.	θ.	Velocity.	H/θ.
35·6	17·0	13·8	2·09
39·6	19·7	12·2	2·01
37·9	19·4	12·2	1·95
33·1	17·0	11·7	1·93
35·2	19·4	10·4	1·81
35·2	19·8	9·05	1·78
33·2	19·4	8·5	1·71
32·0	19·6	7·4	1·63
31·1	20·0	6·8	1·55
31·5	19·7	6·7	1·60
31·3	19·6	6·7	1·59
30·2	19·4	6·5	1·56
31·6	20·5	6·5	1·53
31·3	19·7	6·3	1·59
28·9	19·6	6·2	1·47
27·9	19·5	5·4	1·43
26·0	19·5	5·0	1·33
21·4	19·5	3·2	1·10
19·7	19·4	2·8	1·02

Part II.—*Evaporative Power in Moving Air.*

Having re-determined the formula for the dry kata in moving air, it became necessary to re-investigate the formula for the cooling of the wet kata in moving air, which was provisionally given in the Royal Society paper cited above.

It was not possible to use the large wind tunnels for any extensive investigation of the wet kata, because these tunnels are placed in very large halls, the temperature and humidity of the atmosphere of which we could not vary at will. After taking some preliminary observations in these tunnels, which gave us indications for the construction of the new formula, we employed a tube 4 feet long and 3 inches in diameter, and a fan which sucked air

through the tube at velocities which could be varied at will. Two gauze screens were fixed in the tube to ensure an equable flow of air, and suitable side openings provided through which (1) the kata, (2) a dry bulb, (3) a wet bulb thermometer, were inserted in order, so that the kata came first and the wet bulb nearest the fan. The thermometers were read immediately before the kata was introduced in each observation of cooling rate.

The whole apparatus was placed in a small chamber, kindly placed at our use by Mr. H. R. Davis, at the works of Siebe, Gorman, Ltd., a chamber in which we could at will vary the temperature and humidity through fairly wide ranges. To determine the velocity of the wind we used the reading of the dry kata and our new formula $H/\theta = 0{\cdot}27 + 0{\cdot}49\sqrt{V}$, taking dry kata readings alternately with wet kata readings in each series of determinations.

To determine humidity we used the readings of the wet and dry bulb thermometers and the tables given by the Royal Meteorological Society. Our results are given in Table 3, and are plotted out in Graph II, and the formula which best fits these appears to be

$$E/(F-f)^{4/3} = 0{\cdot}85 + 0{\cdot}102\ V^{0\cdot3},$$

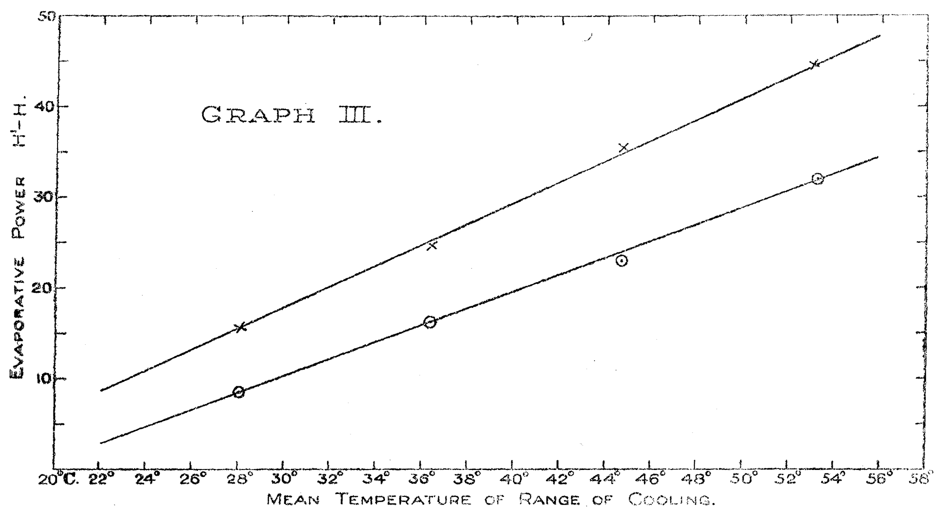
where E = the cooling power due to evaporation, F = the vapour tension in mm. Hg. at 36·5° C. (the mean temperature of the kata surface), f = the vapour tension of the air, and V = the velocity of movement of the air in metres per sec. The full formula for the wet kata is then

$$H = (0{\cdot}27 + 0{\cdot}49\sqrt{V})\,\theta + (0{\cdot}85 + 0{\cdot}102\ V^{0\cdot3})(F-f)^{4/3}.$$

The method available to us only allows an approximate fit to be obtained, firstly, because the velocity is not measured at the same time as the cooling of the wet kata, but just before and after, and the electric power driving the fan may vary slightly; secondly, because the relatively sluggish thermometers may not indicate slight changes in air temperature and humidity, which the excessively sensitive wet kata responds to; thirdly, because the tables, from which the vapour tension is deduced from wet and dry bulb temperatures, are admittedly only approximately correct; fourthly, because of errors in time, the wet kata cooling very rapidly. Error might also arise if too thick a cover was used for the wet kata, and an excess of hot water retained around it. We avoided any such error by using a muslin finger stall. After warming in the Thermos flask, excess of water was removed by gripping the glove above the bulb and drawing it up tightly, and giving the kata one or two downward shakes. Using these means, successive readings of the wet kata gave closely concordant results.

We cannot claim that the formula allows us to determine correctly either

f or V from wet kata readings, but it does allow us to determine approximately from known data of f and V given in meteorological records, what would be the evaporative cooling power. We only propose to use it for that purpose. Using in addition to the ordinary kata one calibrated from 90° to 75° F., and another from 110° to 130° F., we investigated the effect of the surface temperature on the evaporative power. Graph III gives the results we obtained in two of our experiments carried out at different air temperatures and vapour tensions. In one case the evaporative power increases from 7 to 34, a difference of 27. In the other case from 15·5 to 44·5, a



difference of 29. The mean surface temperature increasing in each case from 28° to 53° C. It follows that not only in evaporation from the skin but in the drying of materials the surface temperature is of great importance. By means of the kata the evaporative power of drying chambers can be investigated and drying processes made exact in place of being empirical.

PART III.—*Effect of Barometric Pressure on the Cooling Power.*

In the Royal Society paper cited above, the question of the effect of barometric pressure on the cooling rate of the kata was briefly considered, and a formula expressing the effect put forward, viz.,

$$H = C\sqrt{p},$$

where p = the pressure and C is a constant at constant values of kata bulb and enclosure temperatures, and H applies only to cooling by convection.

Then
$$\frac{\delta H}{H} = \frac{1}{2}\frac{\delta p}{p},$$

Table 3.

Temperature.		Dry kata. H.	36·5−t. θ.	H/θ.	Wind velocity. Metres per sec.	With kata. H′.	H′−H.	Vapour pressure. f.	F−f.	$\frac{H'-H}{(F-f)^{4/3}}$.
Wet bulb.	Dry bulb.									
10·8	14·6	37·7	21·9	1·72	8·76	73·3	35·6	7·6	38·0	0·279
10·9	14·6	36·2	21·9	1·65	7·93	66·9	30·7	7·7	37·9	0·241
10·7	14·4	35·2	22·1	1·59	7·26	65·3	30·1	7·7	37·9	0·236
21·4	23·8	19·6	12·7	1·54	6·73	41·9	22·3	17·1	28·5	0·256
22·9	25·2	16·9	11·3	1·49	6·20	37·9	21·0	18·8	26·8	0·262
10·7	14·4	33·0	22·1	1·49	6·20	65·3	32·3	7·7	37·9	0·255
17·0	19·6	24·6	16·9	1·46	5·90	47·6	23·0	12·7	32·9	0·218
20·2	25·6	12·9	10·9	1·41	5·41	36·9	24·0	13·8	31·8	0·238
10·7	14·4	30·7	22·1	1·39	5·23	59·5	28·8	7·7	37·9	0·226
18·2	25·5	15·0	11·0	1·36	4·95	46·9	31·9	11·3	34·3	0·286
24·6	27·0	12·3	9·5	1·30	4·42	29·6	17·3	20·8	24·8	0·239
10·7	14·4	28·5	22·1	1·28	4·25	59·5	28·8	7·7	37·9	0·226
13·3	16·6	25·5	19·9	1·28	4·25	49·5	24·0	9·4	36·2	0·206
23·4	26·0	12·6	10·0	1·26	4·08	31·1	18·5	19·2	26·4	0·231
18 5	22·7	17·2	13·8	1·25	4·00	41·3	24·1	12·7	32·9	0·229
17·2	25·5	13·4	11·0	1·22	3·76	44·8	31·4	10·2	35·4	0·270
13·7	20·4	19·5	16·1	1·21	3·68	48·6	29·1	8·2	37·4	0·238
16·0	18·9	20·7	17·6	1·18	3·45	42·4	21·7	11·5	34·1	0·196
18·2	22·3	16·1	14·2	1·14	3·15	40·7	24·6	12·7	32·9	0·233
15·5	21·0	17·6	15·5	1·14	3·15	43·8	26·2	10·0	35·6	0·223
18·8	26·0	11·8	10·5	1·12	3·08	40·5	28·7	11·0	34·6	0·255
17·2	25·5	11·9	11·0	1·09	2·80	39·7	27·8	10·2	35·4	0·239
16·7	20·2	17·7	16·3	1·09	2·80	40·8	23·1	11·3	34·3	0·207
23·7	26·4	10·9	10·1	1·08	2·73	28·4	17·5	19·4	26·2	0·225
24·2	26·6	10·6	9·9	1·07	2·67	26·9	16·3	20·5	25·1	0·222
19·5	22·0	15·1	14·5	1·04	2·47	39·0	23·9	14·9	30·7	0·249
13·8	20·5	16·4	16·0	1·02	2·34	43·8	27·4	8·2	37·4	0·218
13·4	16·6	19·9	19·9	1·00	2·22	42·1	22·2	9·4	36·2	0·184
19·2	27·4	8·8	9·1	0·97	2·04	34·3	25·5	11·6	34·0	0·237
24·1	25·5	10·4	11·0	0·95	1·93	25·2	14·8	21·1	24·5	0·208
18·8	23·0	12·8	13·5	0·95	1·93	33·8	21·0	13·5	32·1	0·206
15·5	21·1	13·4	15·4	0·87	1·50	38·2	24·8	10·1	35·5	0·213
13·4	17·2	15·7	19·3	0·82	1·26	38·2	22·5	9·3	36·3	0·187
18·9	26·0	8·2	10·5	0·78	1·08	29·5	21·3	12·0	33·6	0·196
15·8	21·4	11·0	15·1	0·73	0·88	32·4	21·4	10·2	35·4	0·184
14·2	20·8	11·4	15·7	0·72	0·84	33·6	22·2	8·5	37·1	0·179
20·0	29·0	5·3	7·5	0·71	0·81	26·7	21·4	11·9	33·7	0·197
21·5	24·3	7·6	12·2	0·62	0·51	21·7	14·1	17·0	28·6	0·161
21·3	23·9	7·4	12·6	0·59	0·43	20·2	12·8	16·4	29·2	0·142
20·7	23·4	7·6	13·1	0·58	0·40	21·6	14·0	16·0	29·6	0·142
20·0	22·8	7·7	13·7	0·56	0·35	21·6	13·9	16·5	29·1	0·155
12·0	15·7	11.4	20·8	0·55	0·33	28·3	16·9	8·5	33·1	0·159
16·0	22·0	8·0	14·5	0·55	0·33	25·1	17·1	10·1	35·5	0·148
18·6	22·0	7·5	14·5	0·52	0·26	20·7	13·2	13·7	31·9	0·130
19·6	22·4	7·3	14·1	0·52	0·26	19·8	12·5	14·8	30·8	0·130

where δH is the increment of heat loss due to a small change in pressure δp, that is to say, the percentage change in rate of heat loss is one half the percentage change in pressure.

We have further investigated this matter in chambers constructed for high pressure and for low pressure observations, into which we could go ourselves together with our apparatus, chambers kindly put at our use by Mr. R. H. Davis, of Messrs. Siebe, Gorman, Ltd., to whom we are much indebted for the help thus rendered.

Since the theory of the loss of heat by the kata by convection shows that the rate of heat loss is proportional to the square root of the density, and therefore of the pressure, other conditions remaining constant, we may write

$$H_c = C\sqrt{p}, \qquad \text{(i)}$$

where H_c = heat lost by convection, p = pressure, and C = a constant. Experimental evidence shows that at ordinary temperatures and pressures half the heat loss of the kata is due to convection and half to radiation Assuming this to be case if H is the total heat lost, H_c that lost by convection, and H_r that lost by radiation, we have, since $H = 0{\cdot}27\,\theta$ (as proved in the Royal Society paper already cited),

$$H_c = \frac{0{\cdot}27\theta}{2} \qquad \text{(ii)} \qquad\qquad H_r = \frac{0{\cdot}27\theta}{2} \qquad \text{(iii)}$$

also from (i)

$$\frac{H_{c_1}}{H_{c_2}} = \sqrt{\frac{p_1}{p_2}} \qquad \text{or} \qquad H_{c_2} = H_{c_1}\sqrt{\frac{p_2}{p_1}}; \qquad \text{(iv)}$$

substituting for H_{c_1} in (iv) from (ii),

$$H_{c_2} = \frac{0{\cdot}27\theta}{2}\sqrt{\frac{p_2}{p_1}}, \qquad \text{(v)} \qquad H_{c_2} = \frac{H_1}{2}\sqrt{\frac{p_2}{p_1}}, \qquad \text{(vi)}$$

where H_1 is the total heat lost at a pressure p_1.

Now the loss of heat by radiation will be unaltered by changes of pressure, therefore if H_2 is the total heat lost at a pressure P_2, H_{c_2} being the loss due to convection, then

$$H_2 = H_{r_2} + H_{c_2}, \qquad \text{(vii)}$$

where H_r is the heat lost by radiation at a pressure p_1; hence substituting in (vii) for H_{c_2} from (vi),

$$H_2 = H_r + \frac{H_1}{2}\sqrt{\frac{p_2}{p_1}},$$

$$= \frac{H_1}{2} + \frac{H_1}{2}\sqrt{\frac{p_2}{p_1}},$$

$$= \frac{H_1}{2}\left(1 + \sqrt{\frac{p_2}{p_1}}\right). \qquad \text{(viii)}$$

To test the accuracy of this formula, experiments were carried out in still air under conditions of increased and diminished pressure. In the former case the value of the pressure was obtained by a gauge reading in pounds, and was only approximate; in the case of diminished pressure a mercury gauge was used reading to tenths of a centimetre. The results obtained are shown in the Table given below. To allow for the variation of temperature which took place, each of the cooling powers H_1 is reduced to that cooling power H_2 which it would have been if the temperature had been 11·7° C., this being the temperature at which the normal pressure (764 mm. or 15 lbs.) reading was taken; the formula used to obtain H_2 being

$$H_2 = H_1 \frac{\theta_2}{\theta_1}.$$

The column H_2 (calculated) gives the values obtained by equation (viii) H_1 being found experimentally to be 6·94 at temperature 11·7° and pressure p_1 764 mm.

The agreement between the experimental and calculated values are close, and this agreement seems to confirm the experimental observation that half the rate of heat loss at ordinary temperature is due to radiation.

Cooling of Kata in Compressed and Rarefied Air.

Mean time of cooling in seconds.	Mean temperature.	Pressure.	H_1.	H_2 (experimental).	H_2 (calculated).
61·7	11·8	29 lbs.	8·10	8·15	8·29
63·8	10·8	22·5 „	7·84	7·57	7·74
72·1	11·7	764 mm.	6·94	6·94	6·94
81·1	12·7	572 „	6·17	6·42	6·47
88·3	12·9	425 „	5·66	5·95	6·05
95·1	13·4	335 „	5·26	5·65	5·77