RADIATION AT DIFFERENT TEMPERATURES

BALFOUR STEWART states in his "Elementary Treatise on Heat" that "Newton was the first to enunciate his views on the cooling of bodies. He supposed that a heated body exposed to a certain cooling cause would lose at each instant a quantity of heat proportionate to the excess of its temperature above that of the surrounding air." In order to prove the fallacy of Newton's supposition, Prof. Stewart presents the following extract from the work of MM. Dulong and Petit:—

Excess of temperature of the thermometer.	Velocity of cooling.
°C	°C
240	10·69
220	8·81
200	7·40
180	6·10
160	4·89
140	3·88
120	3·02
100	2·30
80	1·74

"We see at once from this table," says Prof. Stewart, "that the law of Newton does not hold, for according to it the velocity of cooling for an excess of 200° should be precisely double of that for an excess of 100°; now we find that it is more than three times as much." The author of the Elementary Treatise on Heat thus assumes that the velocity of cooling established by Dulong and Petit represents the radiant energy or quantity of heat transmitted by the radiator. Consequently, the amount of energy at 200° is assumed to be $\frac{10·69}{1·74} = 6·14$ times greater than at 80°; while, agreeably to Newton's law, the increase of radiant energy should be proportional to the differential temperature, viz, $\frac{240}{80} = 3$ times that of the tabulated temperature of 80°. Modern research having established that radiant heat is energy amenable to the laws of dynamics, it may be demonstrated that the deviation from the Newtonian doctrine assumed by Dulong and Petit is groundless; but, before considering the theory, let us examine the practical result of recent elaborate experiments conducted with an apparatus containing the spherical radiator adverted to in the preceding article on Solar Temperature (vol. v. pp. 505-507). The accompanying illustration (Fig. 1) represents a vertical section of the said apparatus, *a* being a spherical vessel 5 inches in diameter, suspended within an exterior casing *b*, filled with water. A spherical radiator, *c*, 2·75 inches in diameter, composed of very thin copper, charged with water and coated with lamp-black, is sustained in the centre of the sphere *a* by means of tubes applied above and below. The upper tube is large enough to admit the bulb of a thermometer, the lower one being only sufficiently large to accommodate a small axle, to which is attached a paddle-wheel, provided with curved paddles, arranged in such a manner that the bulb of the thermometer may be inserted considerably beyond the centre of the sphere, as shown in the illustration. The external casing *b* is provided with nozzles, *g* and *d*, to which tubes are attached for circulating cold water through the annular space during experiments. The air is exhausted from the spherical enclosure through the tube *k*, which passes across the annular space. It will be evident that the centrifugal action of the paddles of the wheel applied within the radiating sphere will produce a continuous current from the centre towards the circumference, the fluid successively passing over and coming in contact with the inside of the thin shell, then returning to the centre to be again thrown off by the centrifugal action. The rotary motion of the water, kept up without intermission round the cylindrical bulb of the thermometer, will evidently render its indication prompt and reliable. It is hardly necessary to observe that the rapid presentation of fresh particles of water promoted by the action of the paddles, will effectually prevent the reduction of temperature to proceed faster at the circumference than at the centre, the radiation at the surface, in virtue of the continuous interchange of particles, affecting almost simultaneously every molecule within the sphere. Consequently the total energy of radiation will be rendered available in reducing the temperature of the contents of the radiator, while the central thermometer will indicate at every instant the precise degree of temperature of the entire mass.*

The mode of conducting the experiment will be seen by the following statement:—A wooden cistern containing 16 gallons, charged with water and crushed ice, is connected by flexible tubes to the nozzles *g* and *d* on opposite sides of the annular space, a pump being applied between the cistern and the said nozzles, by means of which the cold water is forced through the apparatus and then returned to the cistern.

In view of the great importance of the question at issue, the investigation has been conducted with the utmost care, four operators having invariably been employed during the experiments, the labour being thus divided: 1st operator regulates the temperature of the water in the cistern by continual agitation and supply of crushed ice from time to time; 2nd operator works the pump at a uniform rate; 3rd operator turns the paddle-wheel, and reads the thermometer under a magnifying glass, calling time for each degree at the instant when the top of the mercurial column is covered by half the thickness of the line on the scale. Lastly, the 4th operator, provided with a Casella chronograph, records the time called. It will be seen presently that, notwithstanding this procedure, there is a slight discrepancy in the ratio of temperature and time, viz., the increment of time for each degree is not regular. Obviously the most practised eye cannot determine exactly at what moment the top of the falling column is half covered by the line on the thermometric scale. Again a perfectly graduated thermometer cannot be obtained. But the discrepancy referred to in reality only disfigures the record, since the computations are based on *mean* time. Referring to the accompanying table, it will be seen that the rate at which the spherical radiator cools has been recorded separately for each degree of differential temperature from 100° to 10°, the enclosure being maintained at a constant temperature of 33°. Regarding the construction of the table, it will suffice to state that the time entered in the fourth column is that shown by the chronograph. It will be evident on reflection that the increment of time for each successive degree of differential temperature expresses very nearly the rate of cooling; but, the recorded times being irregular, from causes already pointed out, the true increment cannot be determined without ascertaining the mean time recorded by the chronograph. This mean time will be found in the fifth column, the true increment, viz., the number of seconds during which the temperature of the radiator falls one degree, being entered in the last column.

Let us now examine the accompanying diagram Fig. 2, in which the ordinates of the curve *a b* represent the observed time for each degree of differential temperature, while the ordinates of the curve *a c* represent the corrected time. The diagram having been constructed with the utmost exactness, in accordance with the temperature and time in the table, mere inspection will show that the observed and corrected times have produced curves nearly identical. Agreeably to Newton's law the rate of cooling is proportional to the excess of temperature of a body above that of the surrounding medium. Hence the increment of time for each degree, in other words, the number of seconds occupied in reducing the temperature of the radiator 1° (inserted in the last column of the table) should be proportional to the differential temperature inserted in the third column. For instance the rate of cooling at a differential temperature of 49° being 39·80 seconds for 1°, it should be $\frac{49 \times 39·80}{31} = 62·90$ seconds for an equal thermometric interval at a differential temperature of 31°. Referring to the table, it will be found that the rate thus computed agrees exactly with the increment of time inserted in the last column opposite the differential temperature 31°.

Applying a similar test to the other differential temperatures and rates of cooling contained in the table, the same exact agreement will be found to exist. Consequently, our table and diagram prove that the rate of cooling is proportional to the differential temperature, thus establishing the correctness of the Newtonian law. Regarding the discrepancy indicated by the slight irregularity of the curve *ab*, the writer attributes the same to the

* It might be supposed that the motion of the water within the radiating sphere, produced by the action of the paddle wheel, will occasion an elevation of temperature tending to render the indication of the central thermometer inaccurate. The requisite speed of the wheel being 30 turns per minute, experiments have been made to ascertain if at that rate heat is produced; but no elevation of temperature has been observed. The diameter of the wheel being 2·37in., the maximum speed of the particles of water produced by the rotation is scarcely 3·8ins. per second, a velocity too small to generate appreciable heat.

difference of emissive power of the radiator at different temperatures. It was stated in the preceding article, (vol. v. pp. 505-507), that the radiant power of one square foot of cast-iron develops 0·080 thermal unit per minute for each degree of differential temperature at 65°, and 0·337 unit at 3,000°; hence that the emissive power is increased $\frac{0·337}{0·080} = 4·21$ times for an increment of 3,000 − 65 = 2,935°. Experiments conducted in the

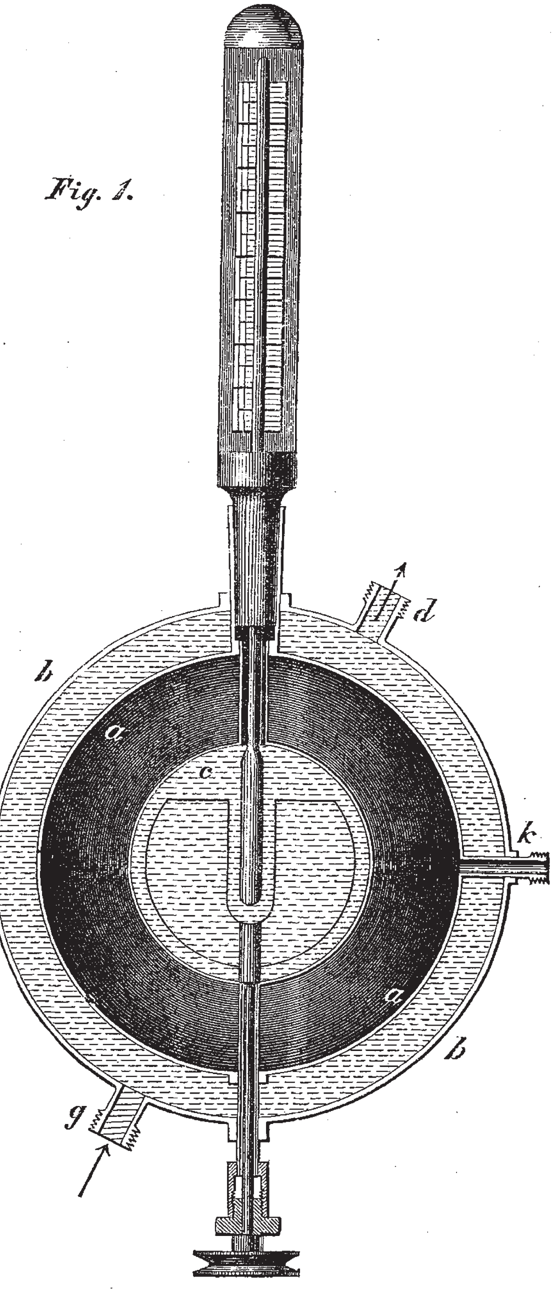

Fig. 1.

mean time show that the radiant power of one square foot of cast iron maintained at a differential temperature of 1,800° is 335 units per minute, hence that the emissive power at this stage of incandescence amounts to $\frac{335}{1,800} = 0·186$ unit for each degree of differential temperature. Our investigations have thus proved that at 65° the emissive power is 0·080 thermal unit, at 1,800° 0·186 unit, and at 3,000° 0·337 for each degree of differential temperature. We have accordingly established the fact that the

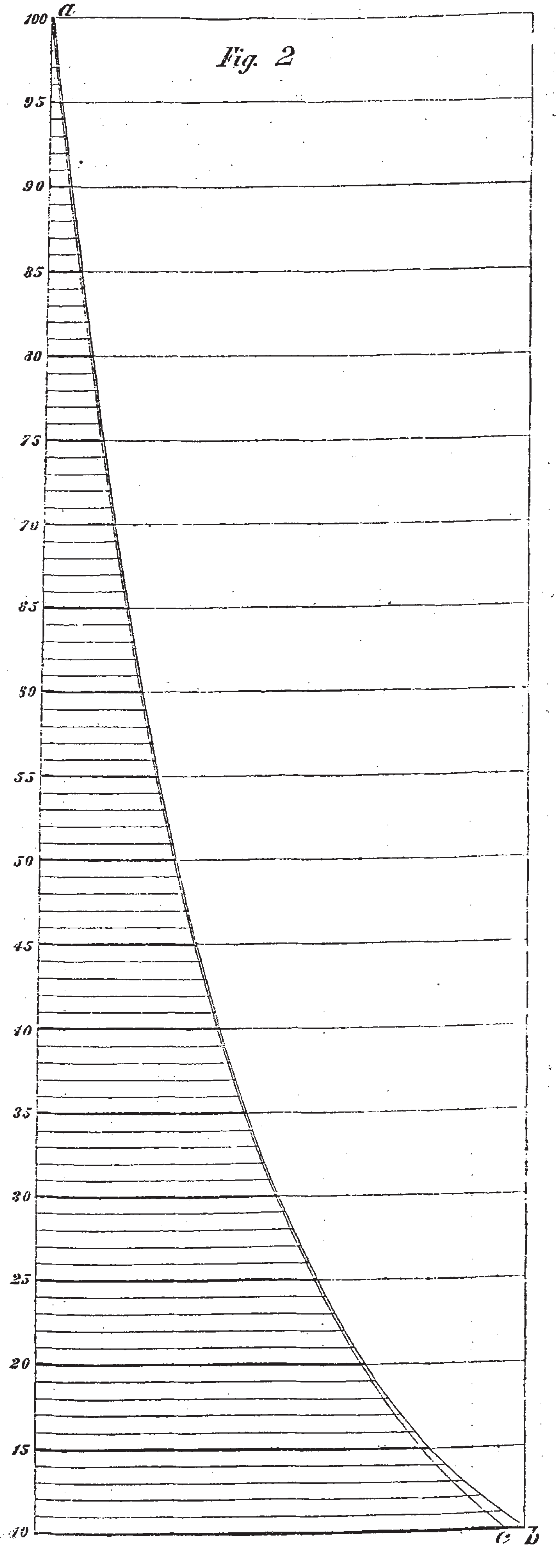

Fig. 2

emissive power increases nearly in the same ratio as the intensities, being fully quadrupled between the differential temperature of 65° and 3,000°. Let us be careful not to confound this increase of emissive power with the increase of radiant energy resulting from mere augmentation of temperature. It is, no doubt, owing to the change of the molecular constitution of the body during heating that the dynamic energy developed at a differential temperature of 3,000° is 4·21 times greater than it should be in accordance with the Newtonian law—a trifling increase, however, compared with that resulting from adopting the computations of Dulong and Petit, whose formula shows that for the stated range of temperature the ratio of radiant energy will be increased more than 4,000 times. It would be premature to attempt to explain the cause of the change of the radiant properties of metals at different temperatures disclosed by our experiments, until further investigations shall have established the exact relation between the actual and theoretical energy developed. Considering the difference of molecular motion within metallic bodies at white heat in a state of fusion, and at the freezing point of water, we need not be surprised at the variation of emissive power observed during our experimental investigation. Nor are we justified, in view of this variation of emissive power, in questioning the correctness of Sir Isaac Newton's assumption that heated bodies of definite radiant properties develop mechanical energies proportional to their excess of temperature over the surrounding media.

Temperature of the radiating sphere.	Temperature of enclosure.	Differential Temperature.	Observed Time.	Corrected Time.	Increment of time for each degree.
Fah.	Fah.	Fah.	Seconds.	Seconds.	Seconds.
133°	33°	100°	19·5	19·50	19·50
132	33	99	39	39·19	19·69
131	33	98	58	59·08	19·89
130	33	97	77	79·18	20·10
129	33	96	97	99·49	20·31
128	33	95	117	120·01	20·52
127	33	94	138	140·75	20·74
126	33	93	158	161·71	20·96
125	33	92	179	182·90	21·19
124	33	91	200	204·32	21·42
123	33	90	222	225·98	21·66
122	33	89	244	247·89	21·91
121	33	88	266	270·04	22·16
120	33	87	288	292·45	22·41
119	33	86	311	315·12	22·67
118	33	85	333	338·06	22·94
117	33	84	356	361·27	23·21
116	33	83	379	384·76	23·49
115	33	82	402	408·54	23·78
114	33	81	425	432·61	24·07
113	33	80	448	456·98	24·37
112	33	79	471	481·66	24·68
111	33	78	495	506·66	25·00
110	33	77	520	531·99	25·33
109	33	76	545	557·65	25·66
108	33	75	571	583·65	26·00
107	33	74	597	610·00	26·35
106	33	73	624	636·71	26·71
105	33	72	651	663·79	27·08
104	33	71	679	691·25	27·46
103	33	70	708	719·10	27·85
102	33	69	737	747·36	28·26
101	33	68	766	776·03	28·67
100	33	67	796	805·13	29·10
99	33	66	827	834·67	29·54
98	33	65	858	864·67	30·00
97	33	64	889	895·14	30·47
96	33	63	920	926·09	30·95
95	33	62	953	957·54	31·45
94	33	61	985	989·51	31·97
93	33	60	1017	1022·01	32·50
92	33	59	1050	1055·66	33·05
91	33	58	1084	1088·68	33·62
90	33	57	1118	1122·89	34·21

Temperature of the radiating sphere.	Temperature of enclosure.	Differential Temperature.	Observed Time.	Corrected Time.	Increment of time for each degree.
Fah.	Fah.	Fah.	Seconds.	Seconds.	Seconds.
89°	33°	56	1152	1157·71	34·82
88	33	55	1188	1193·16	35·45
87	33	54	1220	1229·27	36·11
86	33	53	1257	1266·06	36·79
85	33	52	1294	1303·56	37·50
84	33	51	1331	1341·79	38·23
83	33	50	1371	1380·79	39·00
82	33	49	1408	1420·59	39·80
81	33	48	1448	1461·22	40·63
80	33	47	1489	1502·71	41·49
79	33	46	1530	1545·10	42·39
78	33	45	1572	1588·43	43·33
77	33	44	1615	1632·75	44·32
76	33	43	1659	1678·10	45·35
75	33	42	1704	1724·53	46·43
74	33	41	1751	1772·09	47·56
73	33	40	1802	1820·84	48·75
72	33	39	1852	1870·84	50·00
71	33	38	1904	1922·16	51·32
70	33	37	1958	1974·86	52·70
69	33	36	2015	2029·02	54·16
68	33	35	2070	2084·73	55·71
67	33	34	2128	2142·08	57·35
66	33	33	2188	2201·17	59·09
65	33	32	2250	2262·11	60·94
64	33	31	2313	2325·01	62·90
63	33	30	2379	2390·01	65·00
62	33	29	2448	2457·25	67·24
61	33	28	2520	2526·89	69·64
60	33	27	2595	2599·11	72·22
59	33	26	2674	2674·11	75·00
58	33	25	2754	2752·11	78·00
57	33	24	2839	2833·36	81·25
56	33	23	2929	2918·14	84·78
55	33	22	3025	3006·78	88·64
54	33	21	3126	3099·64	92·86
53	33	20	3232	3197·14	97·50
52	33	19	3343	3299·77	102·63
51	33	18	3459	3408·10	108·33
50	33	17	3581	3522·80	114·70
49	33	16	3715	3644·67	121·87
48	33	15	3859	3774·67	130·00
47	33	14	4015	3913·95	139·28
46	33	13	4185	4063·95	150·00
45	33	12	4370	4226·45	162·50
44	33	11	4571	4398·73	177·28
43	33	10	4792	4593·73	195·00

J. ERICSSON

[WE have received a communication by cable from the author, to the effect that the engraver has indicated, in Fig. 2, a continuous space between the curves *a b* and *a c*, whereas the space should cease at one portion, the curves intersecting each other between the ordinates 25 and 30. The mistake is so trifling that it can scarcely be observed with the naked eye, yet it will no doubt be detected by such men as Stewart, Maxwell, and Everett. It is to be found, on looking at the table, that the observed times are shorter than the calculated times at the high temperatures, while the observed times are longer than the calculated times at low temperatures; hence the curves must intersect each other.—ED.]

NOTES

THE *Pall Mall Gazette* states that the Earl of Portsmouth, who is the collateral representative of Sir Isaac Newton, has offered to the University of Cambridge, through the Duke of Devonshire (Chancellor of the University), all the papers of Sir