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On the Heat Dissipated by a Platinum Surface at High Temperatures. Part IV. Thermal Emissivity in High-Pressure Gases

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VI. *On the Heat Dissipated by a Platinum Surface at High Temperatures. Part* IV. *Thermal Emissivity in High-pressure Gases.*

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Contents.

PART IV.*

Thermal Emissivity in High-pressure Gases.

The question of the heat dissipated by a hot body in gases at ordinary pressures has received considerable attention during recent years. The subject has been

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* For Parts I., II., III. see 'Philosophical Transactions of the Royal Society,' A, vol. 191, p. 501, 1898.
Part I. was entitled "Emissivity of a Bright Platinum Surface in Air and other Gases."
Part II. ,, "A Bolometric Study of the Law of Thermal Radiation."
Part III. ,, "On the Variation of the Intrinsic Brilliancy of Platinum with Temperature."

experimentally treated in many different ways. The rate of cooling of a body of known specific heat has been directly measured by DULONG and PETIT, NARR, MACFARLANE, NICHOL, STEFAN, BRUSH, BOTTOMLEY, WINKELMANN, KUNDT, and WARBURG, ECKERLEIN, GRAETZ, &c. By CHRISTIANSEN'S method, the value of the conductivity has been derived from the fall of temperature per unit length along the axis of a cylinder carrying a constant flow of heat. SCHLEIERMACHER, SALA, AYRTON, and others have preferred to measure the quantity of electrical energy dissipated per unit time. These experiments have, however, been carried out at or below the atmospheric pressure, and the question of the heat dissipated in gases at high pressures has rarely been touched upon. From the ordinarily accepted principles of the Kinetic theory of gases, it may be shown that the conductivity of any perfect gas is independent of pressure. The experimental work of STEFAN and of KUNDT and WARBURG has gone far to confirm this law as far as ordinary pressures are concerned. It will be seen, however, that at higher pressures, only a small proportion* of the loss of heat is due to conductivity, and the question as to whether the theoretical law is strictly correct, though well worth investigation, is not of primary importance.

For the above reasons the present work has been restricted to a study of the total heat dissipated at exceptionally high pressures and temperatures.

The Apparatus.

The method employed is the same as that described in 1898 in the first part of the present series. It will therefore be sufficient to recall here that the measurements are made by means of a wire, calibrated as an electric thermometer according to CALLENDAR'S system, and heated by an electric current, the readings of the current passing through the wire, and the electromotive force at the potential terminals, being made by a potentiometer. The standard resistance had a temperature coefficient of 0·000003, and as it was efficiently cooled, the small outstanding variations in temperature involved no correction.

The results of the comparison of this coil (0·01 ohm, WOLFF, No. 779) with two standards of reference (0·1 ohm, No. 709, and 0·001 ohm, No. 834) are given below :—

	Standard 0·1 ohm in terms of the working standard.	Standard 0·001 ohm in terms of the working standard.
On the 27th September, 1895 . .	10·005	0·10004
On the 3rd March, 1900	9·985	0·09991

The original resistance of the working standard was, according to the Reichsanstalt Certificate, 0·0099967 at 24°·9 C. and 0·0099965 at 16°·5 C. On the 3rd March, 1900, its resistance having increased about 0·16 per cent., was therefore

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* About $\frac{1}{16}$th at 160 atmospheres.

0·010012 ohm. From similar observations it was deduced that the electromotive force of the CLARK's cell (No. 5217 A) had fallen by 0·2 per cent. during the last two years. The variations being in opposite directions tend to cancel, and the outstanding error as far as the energy measurements are concerned is not sufficient to affect the results. On the other hand the temperature measurements are, of course, independent of the absolute value of the standard.

The CLARK's cell was kept in the inner chamber of a Berthelot calorimeter; only very slow variations of its temperature were therefore possible, and the agreement of the electromotive force with the temperature indicated by the attached thermometer was thus ensured.

The enclosure was formed by a steel cylinder 6·0 centims. in outside diameter and 2·06 centims. bore and 45 centims. long (see fig. 1). It was surrounded by a water jacket. The temperature of the enclosure was estimated by a thermometer, the spherical bulb of which just fitted a hole drilled in the walls of the steel cylinder, half-way along its length; the depth of the hole being such that the bulb was equidistant from the inside and outside face of the wall. After the thermometer was in position the hole was filled with mercury to ensure satisfactory contact.

The ends of the steel enclosure were closed by the fibre plugs (P_1, P_2, fig. 1), held in position by the gun-metal nuts, N_1, N_2. The current was led in and out by the copper bars, B_1, B_2 (about 1 centim. in diameter), passing through the centre of the plugs. One end of the radiating wire R was silver-soldered to the copper terminal B_1, the other end was connected to B_2 by a flexible connection (200, No. 40, S.W.G.). The radiating wire was kept taut by means of the light spring S. One of the potential terminals T_1 was connected to the steel cylinder, the other kept insulated and passed through the fibre plug P_1. The enclosure was kept at a constant temperature by means of a water circulation.

The same pure platinum wire was used as a radiator

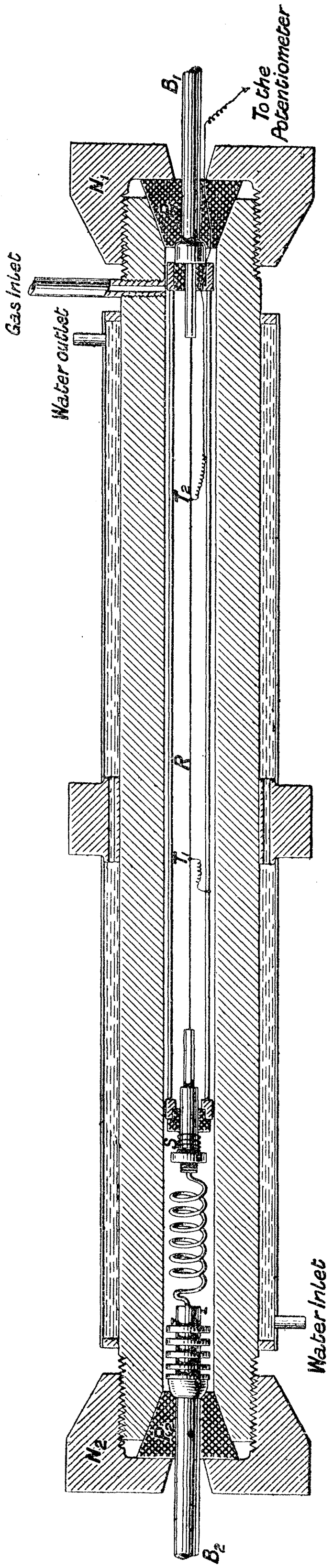

Fig. 1. Scale = about $\frac{1}{3}$.

in all the experiments, but owing to two slight accidents the calibration is not quite the same throughout. The wire was calibrated four times during the course of the work.

It is, of course, necessary to eliminate the cooling effect of the terminals, and to ensure this, the heat dissipated by the middle third of the wire was alone measured. In the experiments made in 1898 the radiating wire was placed vertically. At the pressure of one or two atmospheres that was then used, consistent results could be obtained by this disposition, and it had the advantage that the wire was an axis of symmetry with regard to the convection currents. At high pressures, however, owing to increased convection, it is impossible to keep a sufficient length of radiating surface at a uniform temperature unless the axis of the radiator is horizontal. For the reasons given in Part I. (see page 506 and Plate 20), the absolute value of the emissivity is rather greater when the radiator is horizontal than when it is vertical.

The pressures recorded were obtained from the readings of an air manometer, which was calibrated in the ordinary way by weighing mercury. The glass manometer tube ended in an air bulb, contained in a strong steel vessel resembling a small Cailletet bottle. The relative volumes of the air bulbs were regulated so that one instrument began reading at 7 atmospheres and the other at 100. The tubes were so arranged that the level of the mercury in the reservoir could be estimated, and the correction for the weight of the mercury column calculated. An ordinary Bourdon gauge was attached to each manometer for convenience of reference during the experiment.

All joints and connections were made metal to metal without intermediate packing. Where high pressures are to be used, the importance of designing the connections in this manner cannot be exaggerated. A metallic joint once made will remain tight for any length of time. And on the other hand, if at any time it is necessary to change the connections, the joint can be broken and re-made in a few minutes.

Experimental Work.

The same routine was observed throughout in taking the observations. The enclosure having been filled with gas at about the required pressure, the water circulations were started. As soon as the temperature had become constant, the pressure of the gas, and the temperatures of the standard resistance, of the pressure gauge, and of the enclosure, were read, and any other observations that might be of importance, such as the barometric pressure, the temperature of the room, of the circulating water, &c., recorded.

In all cases two readings of the current and electromotive force were taken, so as to cancel any thermo-electric effects by reversing the current. The differences in the readings shown in Table I. were due in great part to inequalities in the resistance of the two sides of the reversing switch. They were in a large degree eliminated in subsequent work. As however the mean of the two readings is always taken, variations of this kind hardly affect the results.

The method of working out the observations has in all cases been identical to that shown in Table I., but for the sake of brevity and clearness the final results have alone been given.

The emissivity expressed in C.G.S. units is equal to the number of therms (water-gramme-degrees) dissipated, per square centimetre of surface of radiator,* per second, per degree Centigrade above the temperature of the enclosure. During the experiments the temperature of the enclosure was usually about 18° C. The results of the observations are recorded in Tables II.–VI. In the case of each series the pressure indicated is the absolute pressure of the gas when no current is passing through the radiating wire. The pressure readings recorded have been corrected for the temperature of the manometer, the height of the mercury column and the departure of air from BOYLE'S law, this latter correction being made according to AMAGAT'S results.

The importance of having some data with regard to the total heat dissipated cannot be denied, but our knowledge of the phenomena is not at present sufficient for a general theory to be evolved. It was therefore thought preferable to reduce the results in such a manner that they should not involve any assumptions which later work might prove to have been unjustifiable. It must be admitted that the emissivity as above defined is dependent to a certain degree on experimental conditions, such as the size and shape of the radiator and enclosure. But the advantage is gained that, with these conditions specified, it is a well-defined quantity, and that when the laws which govern the transfer of heat through high-pressure gases become accurately known, the generalisation of the present results will present no difficulties. The choice of the size of the radiator and enclosure was made with a view to minimise the objection that has been pointed out.

Before passing to other considerations, two possible causes of error require investigation. If what SMOLUCHOWSKI DE SMOLAN† has called the discontinuity of temperature—the equivalent of what is known to electricians as contact resistance—exists between the enclosure and the contained gas, the observations will give results too low.

This effect, however, is inversely proportional to the pressure of the gas, and above 1 atmosphere would correspond to an effective increase in the radius of the enclosure of less than 0·00001 centim. It need not, therefore, be brought into consideration.

A more serious cause of error lies in the fact that the walls of the enclosure being 2 centims. thick, the inside surface might be considerably above the tempera-

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* All the results are referred to the area of the radiator as measured at a temperature of about 18° C.

† 'Phil. Mag.', vol. 46, p. 192, 1898; also E. WARBURG and E. GEHRKE, 'Annalen der Physik,' 4th s., vol. 2, p. 102, 1900.

ture indicated by the thermometer; this again would cause the emissivity to be under-estimated. Taking the maximum values of the temperature and pressure, we find that in air at 160 atmospheres and 1200° C. the emissivity is 0·01259, and the heat dissipated $= \mathrm{E}\vartheta\pi.d = 5{\cdot}249$ C.G.S. units per second, per unit length. The inside diameter of the enclosure is 2·06 centims., its superficial area 6·472 sq. centims. per unit length. Taking the conductivity of steel as 0·11, this would correspond to a fall of temperature of 7°·3 C.

Thus the temperature interval we estimated at 1200, really was 1193. This cause of error would be very serious were it not for the fact that it decreases not only with the square of the temperature but also with the pressure. At 160 atmospheres and 500° C. the flow of heat is 1·612 C.G.S. units, making the error 2°·3 C.; at 100 atmospheres and 500° C. the error is 1°·6 C., and for 30 atmospheres and 500° C. = 1°·0 C.

Over the greater part of the range of observation the error due to this cause is therefore below one-third per cent., but it rises to about two-thirds per cent. at the highest temperatures and pressures

Results obtained.

In all cases the heat dissipated by a hot body surrounded by gas is the sum of three distinct quantities, all three being functions of the temperature, and one at least being also a function of the pressure. The formula for the total radiation expressed in words will therefore read—

$$\text{Total heat dissipated} = \text{Convection} + \text{Conduction} + \text{Radiation}.$$

$$\text{Or Emissivity} = \mathrm{F}_1(p, t) + \mathrm{F}_2(t) + \mathrm{F}_3(t) \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(i.)}.$$

Of these four quantities, two, Conductivity and Radiation, have been determined by previous experimenters, and the determination of a third will enable us to solve the equation for any value of t or p. The heat carried off by convection not being directly measurable, our only resource is to determine it by difference.

The experimental results will be found plotted in figs. 2 to 6. It will be seen that in all cases above about 10 atmospheres the emissivity is practically a linear function of the temperature, from which fact we conclude that the loss by radiation must be relatively very small. We may therefore write for any given pressure

$$\mathrm{E} = m + n\vartheta.$$

Both the values m and n increase as the pressure rises: closer observation shows that for any one gas they may be expressed as exponential functions of the pressure. We thus obtain for the total emissivity an expression of the form

$$\mathrm{E} = ap^{\alpha} + bp^{\beta}\vartheta \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad \text{(ii.)},$$

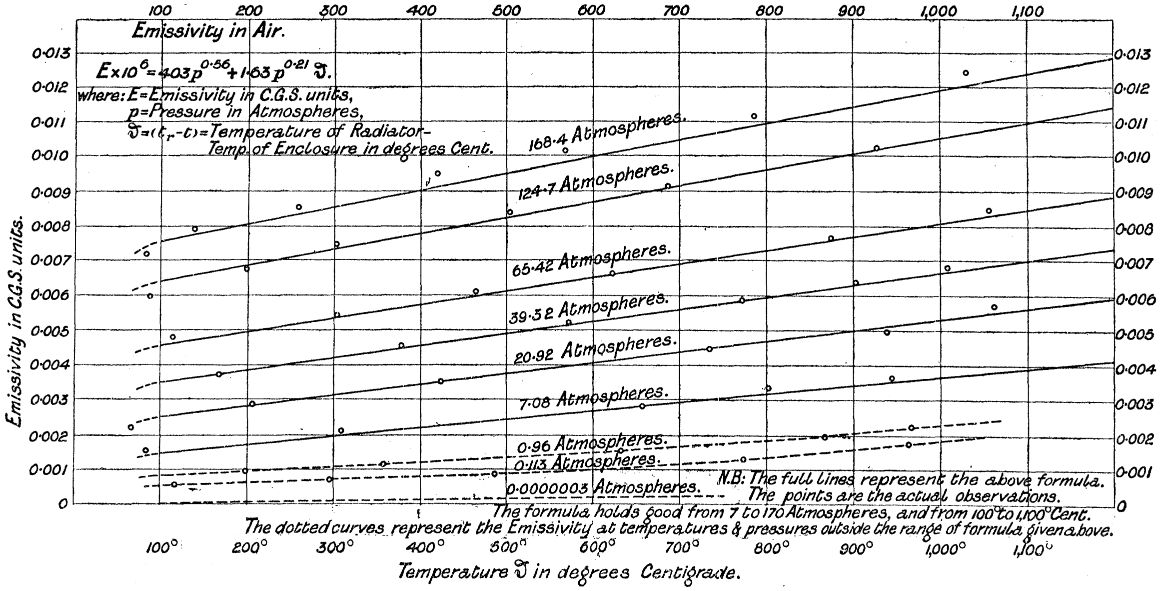

Fig. 2.

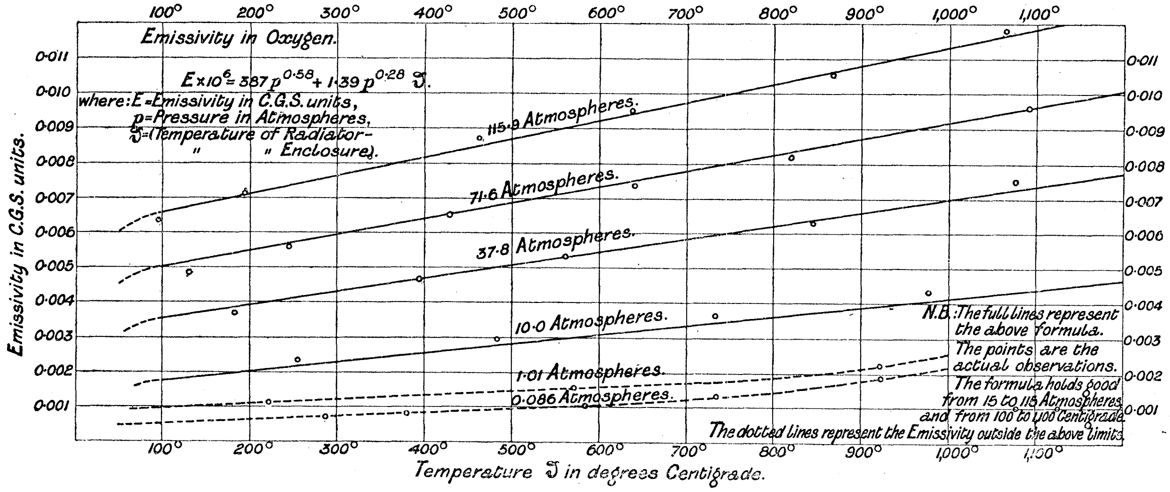

Fig. 3.

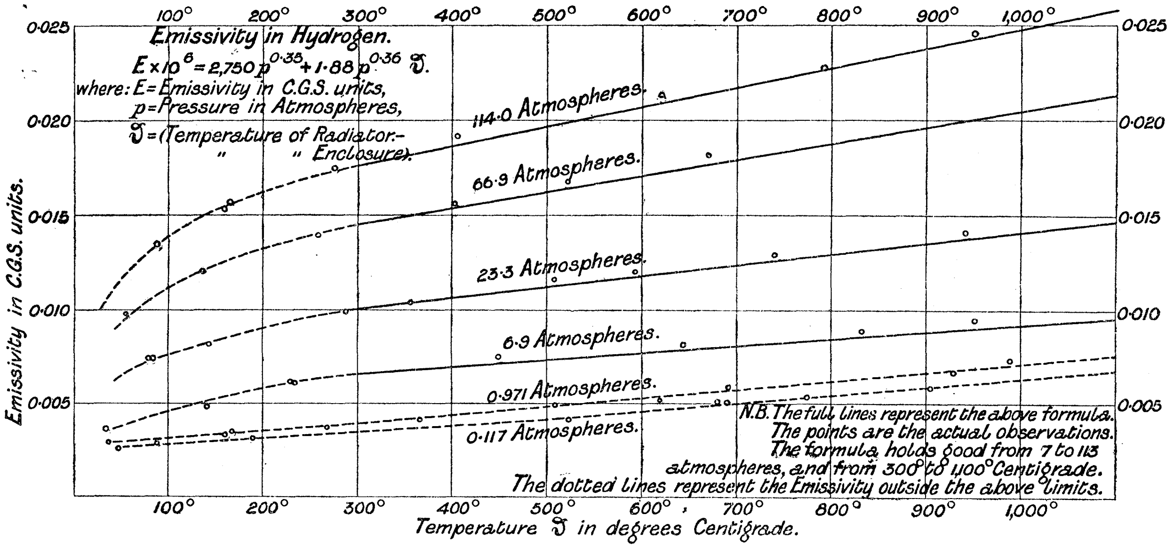

Fig. 4.

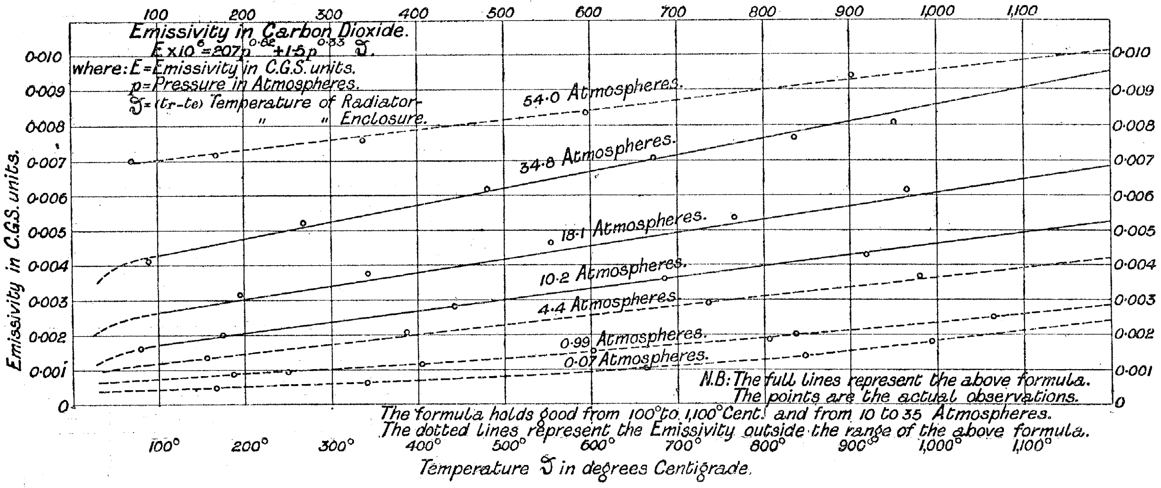

Fig. 5.

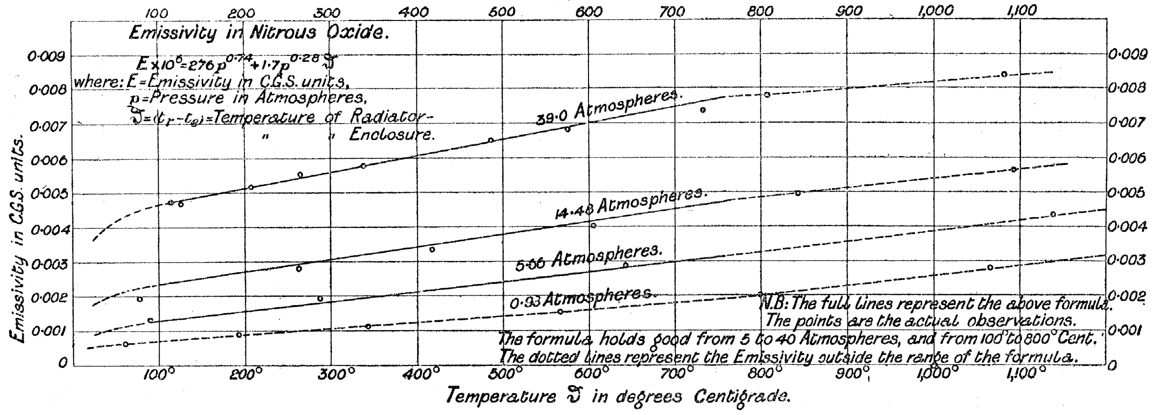

Fig. 6.

where E = emissivity in C.G.S. units, p = pressure in atmospheres, ϑ = (Temperature of the Radiator—Temperature of the Enclosure) in degrees C. The values of the constants a, b, α and β, are given in the following table:—

	$a \times 10^6$.	$b \times 10^6$.	α.	β.	The formula holds good			
					From ϑ =	To ϑ =	And from p =	To p =
Air	403	1·63	0·56	0·21	100	1100	7	170
Oxygen . . .	387	1·39	0·58	0·28	100	1100	15	115
Hydrogen . . .	2750	1·88	0·35	0·36	300	1100	7	113
Nitrous oxide .	276	1·70	0·74	0·28	100	800	5	40
Carbon dioxide .	207	1·50	0·82	0·33	100	1100	10	35

In figs. 2 to 6 the full lines represent the formulæ, the constants of which have just been given; the points are the actual observations. The agreement between the calculated and observed results will be seen to be satisfactory.

The increase of emissivity with pressure in the case of air is shown in fig. 7.

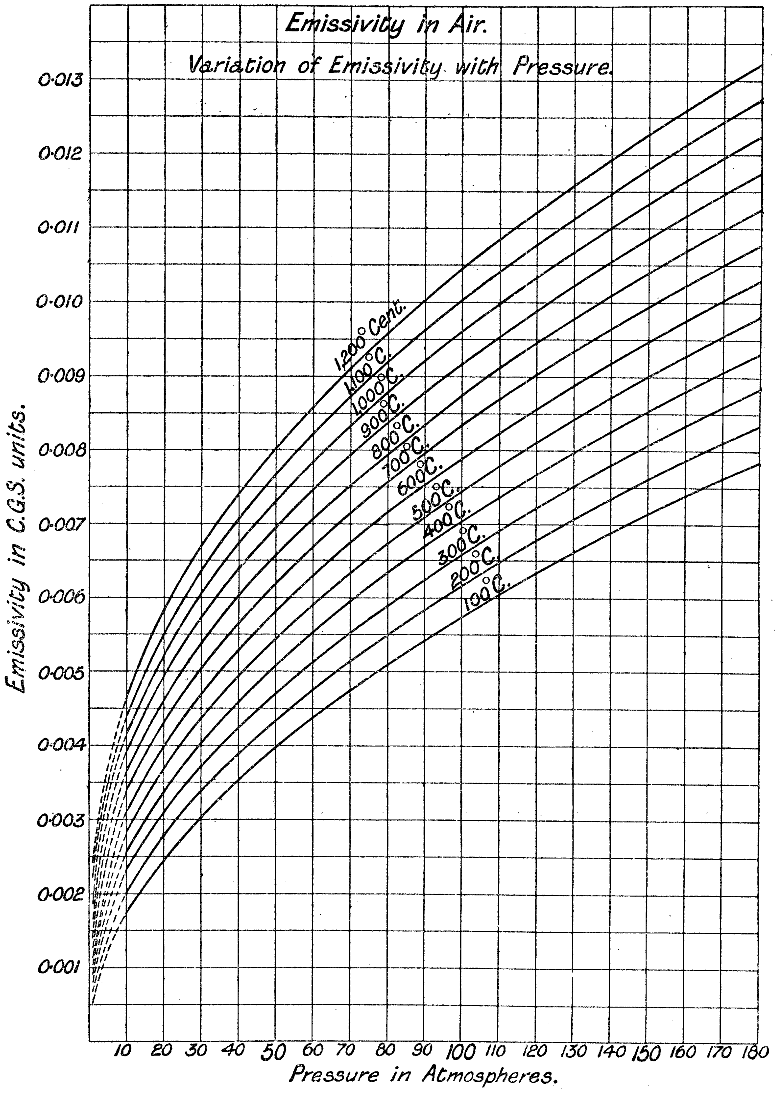

Fig 7.

On the Variation of Emissivity with Pressure.

To return to the general formula for the heat dissipated. From the results so far obtained, we may write for pressures above 10 atmospheres

$$\text{Emissivity} = ap^{\alpha} + bp^{\beta}(t_r - t_e) = \mathrm{F}_1(p, t) + \mathrm{F}_2(t) + \mathrm{F}_3(t),$$

and therefore

$$\left.\begin{array}{l}\text{Heat lost by convection}\\ \quad\text{in therms per sq.}\\ \quad\text{centim., per degree}\\ \quad\text{temperature interval,}\\ \quad\text{per second}\end{array}\right\} = \left[ap^{\alpha} + bp^{\beta}(\mathrm{T}_r - \mathrm{T}_e)\right] - \left[\mathrm{C}_1 k(1 + n\mathrm{T}_r)\right] - \left[\mathrm{C}_2 \frac{\mathrm{T}_r^4 - \mathrm{T}_e^4}{\mathrm{T}_r - \mathrm{T}_e}\right] \quad . \quad . \quad . \quad \text{(iii.)},$$

where a, α, b, β, C_1, k, $n_1\mathrm{C}_2$ are constants, p the pressure, and T_r and T_e the absolute temperatures of the radiator and the enclosure.

The numerical values of each of these three terms of the above equation[*] for air at temperatures between 100 and 1000 and pressures between 10 and 160 atmospheres will be found in Table VII., and the values of the emissivity for the other gases studied are recorded in Tables VIII. to XI.

If we consider the temperature constant, we obtain for the variation of emissivity with pressure :[†]

$$\mathrm{E} = ap^{\alpha} + b_1 p^{\beta},$$

and we have seen that the exponents of p are different for every gas studied. It is not easy to reconcile this fact with the theory that conductivity, viscosity, and specific heat are all three independent of pressure. It must be remembered, however, that the theory is deduced on the assumptions that the molecular paths are straight lines, that the radius of the molecular sphere of action is very small compared with the mean free path, and that the cohesion of the gas is a negligible quantity.

Neither of these hypotheses seems altogether justifiable at pressures of one or two hundred atmospheres.

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[*] The numerical value of the heat lost by conductivity is merely given to show that, as far as our present knowledge goes, it forms a very small proportion of the total loss observed at high pressures. Though the conductivity of gases at ordinary pressures is fairly accurately known its temperature coefficient is as yet uncertain. No observations are available above 200° C., and even at lower temperatures there is much discrepancy between different observers. For air, for instance, WINKELMANN gives 0·0019, EICHHORN 0·00199, SCHLEIERMACHER 0·0028, and ECKERLEIN 0·0036. Again, the effective temperature of the gas is uncertain, but to make sure of not under-estimating the part played by conductivity we have used the maximum value T_r.

[†] DULONG and PETIT ('Annales de Chimie et de Physique,' 1st s., vol. 7, p. 337, 1817) found for the loss due to convection and conduction per degree temperature interval

$$\mathrm{N}p^{\alpha_1}\,\vartheta^{1\cdot233}.$$

At constant temperature the variation with pressures would be

$$a_1 p^{\alpha_1},$$

where a_1 = a constant, p = pressure, α_1 = 0·45 for air, 0·38 for hydrogen, and 0·517 for CO_2.

In the formula (ii.) above $\frac{b}{a}$ is of the order $\frac{1}{200}$, and for small values of ϑ, the emissivity is approximately equal to

$$a_2 p^{\alpha},$$

where a_2 = a constant, p = pressure, and α (see p. 236) is 0·56 for air, 0·35 for hydrogen and 0·82 for

The results of WARBURG and VON BABO* have shown that for gases near their critical temperature, there is a great increase of viscosity as the critical pressure is approached.

MEYER explains, and at the same time confirms this result, by a calculation based on the assumption that the gas is a mixture of double and simple molecules.

The relatively large value of the exponents of p (see page 236) in the case of carbon dioxide and nitrous oxide, may be accounted for by the above fact.

It has been shown that the conductivity of a gas is proportional to its viscosity. Taking into account that even the so-called permanent gases diverge considerably from BOYLE'S law at the higher pressures, it seems probable that the constancy of this conductivity is far from absolute.

A glance at figs. 2 to 6 will show that in every case a sharp fall occurs in the curve of emissivity when ϑ decreases below a certain limit;† and from such measurements as have been made at small temperature intervals there can be no doubt that at pressures above 10 or 20 atmospheres the conductivity accounts for only a very small proportion of the total heat dissipated, but none the less the conductivity may have considerably increased in absolute value.

The present experiments do not, therefore, definitively settle the question. To eliminate convection at the higher pressures, the temperature interval between the radiator and the enclosure would have to be a small fraction of a degree. An apparatus designed to measure up to 1000 degrees is not suitable for this kind of work. It was therefore thought preferable to leave the subject for a future investigation, rather than record values which would only be a rough approximation.

On the other hand, at ordinary pressures the constancy of the conductivity has received ample experimental verification, and there is no difficulty in determining the absolute amount of heat lost by each of the three factors: radiation, convection, and conduction.

An Analytical Study of the Total Heat Dissipated.

Our first object must be to determine what proportion of the total loss is due to conduction alone.

In the present case we have two coaxial cylinders: the one forming the radiator, the other the enclosure, and we must determine what is the thermal conductance of the air filling the intervening space.

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carbon dioxide. When it is taken into account that DULONG and PETIT'S formula was derived from observations made at pressures below 1 atmosphere and under totally different experimental conditions, even this approximate agreement is not devoid of interest.

* 'Wied. Ann.,' vol. 17, p. 390, 1882.

† About 300° for hydrogen and 100° for all other gases.

Let us divide this space into a number of concentric cylinders, having a length l equal to the distance between the potential terminals of the wire and a thickness Δr.

The thermal resistance of each of these cylinders will be

$$= \frac{\Delta r}{l 2 \Pi r} \times \frac{1}{K},$$

where r is the radius of the cylinder and K the conductivity of the gas under consideration, in this case air.

The total thermal resistance will therefore be

$$= \frac{1}{2 \Pi l K} \int \frac{dr}{r}.$$

Integrating between the limits $r = R =$ radius of the enclosure and $r = r_1 =$ radius of the radiator, we have

$$\text{Total resistance} = \frac{1}{2 \Pi l K} (\log_e R - \log_e r_1),$$

or the conductance $= \dfrac{K 2 \Pi l}{\log_e R - \log_e r_1} =$ Total flow of heat per degree Centigrade of temperature interval per second.

Now the emissivity is defined as the flow of heat per unit surface of radiator per degree Centigrade per second, and the above expression divided by the superficial area of the wire will thus be equal to the part of the emissivity due to conduction alone.

$$E_c = \frac{K 2 \Pi l}{2 \Pi r_1 l (\log_e R - \log_e r_1)} = \frac{K}{(\log_e R - \log_e r_1) r_1} \quad . \quad . \quad . \quad . \quad . \quad \text{(iv.)},$$

where E_c is the part of the emissivity due to conduction alone. In the present case $r_1 = 0{\cdot}0553$, $R = 1{\cdot}03$, thus:

$$E_c = \frac{K}{0{\cdot}1617}.$$

Inversely, if the convection is zero and the radiation = R,

$$0{\cdot}1617 (E - R) = K = \text{conductivity}.$$

By measuring the emissivity at low temperatures and pressures, we can reduce, though not entirely suppress convection, and, by subtracting the heat lost by radiation, obtain a comparison with the standard determinations of the conductivity of gases. The value thus calculated will always be in excess of the true conductivity of the gas by an amount proportional to the heat lost by convection.

In the following table E is the emissivity at 100° C., and 0·1 atmosphere; R the radiation calculated from J. T. BOTTOMLEY'S experiments,* and K_{100} is the conductivity at 100° C. according to WINKELMANN :—

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* 'Roy. Soc. Proc.,' vol. 66, p. 276, 1900.

	Air.	Oxygen.	Hydrogen.	Carbon dioxide.
E	0·00050	0·00052	0·00285	0·00044
E—R	0·00047	0·00049	0·00282	0·00041
0·1617 (E—R) . . .	0·000076	0·000079	0·000456	0·000066
K_{100}	0·000067	0·000066	0·000455	0·000046
Heat lost by convection × 0·1617 .	0·000009	0·000013	0·000001	0·000020

The fact thus brought out, that the convection is a maximum in carbon dioxide and a minimum in hydrogen,* may cause some surprise, for the coefficient of viscosity of the former is only half that of the latter. It must, however, be remembered that the force causing convection is the buoyancy of the heated gas which is proportional to its density. The heat conveyed by the stream of gas is proportional to the volume of the gas in motion, its mean rise of temperature, its mean velocity, its specific heat, and its density; thus we have for a given temperature†

$$\text{Convection} = A\,\frac{\rho^2 C}{\gamma}.$$

Where A = a constant, ρ = the density of the gas, C = the specific heat, γ = the viscosity.

According to the above formula, the relative convection in carbon dioxide, oxygen, air, and hydrogen is represented by the numbers 20, 8·6, 8·5, and 1·2. If we take into consideration that the experimental numbers 0·000020, 0·000013, 0·000009, and 0·00001 are obtained from the difference of two nearly equal quantities, the agreement may be considered satisfactory.

We are now in a position to express in absolute units the heat lost respectively by convection, conduction, and radiation.

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* This fact is confirmed by the experiments of KUNDT and WARBURG (see 'Pogg. Ann.,' vol. 156, p. 179, 1875). They found that, in a certain apparatus, the heat dissipated was independent of pressure up to 30 millims. in the case of air, and up to 154 millims in the case of hydrogen.

† This relation between the heat lost by convection and the density, viscosity, and specific heat of a gas only holds good when the speed of the convection currents is very low; at higher temperature and pressures the phenomenon is more complex.

At one-tenth of an atmosphere and 100° C., we have for the various gases—

Pressure, 0·1 Atmosphere. Temperature interval, $\vartheta = 100°$ C.*

Heat lost—	Air.		Oxygen.		Hydrogen.		Carbon dioxide.	
	In C.G.S. units.	In per cent.	In C.G.S. units.	In per cent.	In C.G.S. units.	In per cent.	In C.G.S. units.	In per cent.
By conduction . . .	0·00041	82	0·00041	79	0·00281	98·6	0·00028	64
By convection . . .	0·00006	12	0·00008	15	0·00001	0·4	0·00013	30
By radiation . . .	0·00003	6	0·00003	6	0·00003	1·0	0·00003	6
Total heat lost = emissivity	0·00050	100	0·00052	100	0·00285	100	0·00044	100

And if, for the present, we assume the conductivity constant the values at 100 atmospheres and 100° C. would be—

Pressure, 100 Atmospheres; Temperature interval, $\vartheta = 100°$ C.*

Heat lost—	Air.		Oxygen.		Hydrogen.	
	In C.G.S. units.	In per cent.	In C.G.S. units.	In per cent.	In C.G.S. units.	In per cent.
By conduction . . .	0·00041	7·1	0·00041	6·7	0·00281	21·4
By convection . . .	0·00530	92·4	0·00566	92·8	0·01026	78·4
By radiation . . .	0·00003	0·5	0·00003	0·5	0·00003	0·2
Total heat lost = emissivity	0·00574	100	0·00610	100	0·01310	100

The result is remarkable; for instance, in the case of air, at one-tenth of an atmosphere 12 per cent. of the total loss is due to convection, and at 100 atmospheres 92 per cent. is due to this same cause. The heat lost by convection is in air 100, and in hydrogen 500 times greater at a pressure of 100 atmospheres than it is at 0·1 atmosphere.

For temperature-intervals of several hundred degrees it is impossible experimentally to eliminate either of the three effects of convection, conduction, or radiation, but the first of the three can be greatly diminished. To this end the apparatus was filled with lightly packed glass-wool. The proportion of the total volume actually occupied by the glass was 2·0 per cent.

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* The loss of heat is expressed in therms per square centimetre of radiating surface, per second per degree Centigrade of temperature interval.

Emissivity in Air.

Gas only.				Convection diminished by filling the enclosure with lightly packed glass wool.			
Temperature ϑ in degrees Centigrade.	Heat dissipated by conduction and radiation.	Emissivity.	Heat dissipated by convection = C.	Heat dissipated by conduction of the glass and air and by radiation.	Emissivity.	Heat dissipated by convection = C_1.	Ratio $\frac{C}{C_1}$.
1·01 atmo. 100	0·00045	0·00084	0·00039	0·00056	0·00071	0·00015	2·60
200	0·00054	0·00095	0·00041	0·00065	0·00082	0·00017	2·41
300	0·00064	0·00106	0·00042	0·00075	0·00093	0·00018	2·33
400	0·00075	0·00119	0·00044	0·00086	0·00105	0·00019	2·32
69·7 atmo. 100	—	0·00474	0·00429	—	0·00176	0·00120	3·58
200	—	0·00513	0·00459	—	0·00217	0·00152	3·02
300	—	0·00553	0·00489	—	0·00235	0·00160	3·06
400	—	0·00593	0·00518	—	0·00247	0·00161	3·22
169 atmo. 100	—	0·00761	0·00716	—	0·00462	0·00406	1·76
200	—	0·00808	0·00754	—	0·00544	0·00479	1·57
300	—	0·00856	0·00792	—	0·00580	0·00505	1·57
400	—	0·00904	0·00829	—	0·00605	0·00519	1·60

As may be seen in the above table the result was to reduce convection to one-half or one-third of its former value. The effect on the total heat lost is of course least at low pressures, at which conduction plays the most important part; the decrease is about 14 per cent. at 1 atmosphere, and twice or three times as much at higher pressures.

On the Influence of Experimental Conditions.

The remaining factors which influence the total amount of heat dissipated are the dimensions of the enclosure and radiator and the temperature of the gas.*

Let us first consider the effect of a change in the diameter of the radiator.

We have found above (p. 240) that the heat lost by conduction is

$$E_c = \frac{K}{(\log_e R - \log_e r)} \frac{1}{r} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (v.),$$

where R is the radius of the enclosure, r the radius of the radiator, and K the conductivity of the gas.

If the ratio $\frac{R}{r}$ is very great we may, within a limited range, consider $\frac{K}{\log_e R - \log_e r}$ as constant and put $E_c = c_1 r^{-1}$.

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* Some experiments on this question were recorded in Part I., but the following additional considerations may be found of interest.

Simultaneously with conduction (*i.e.*, the dissipation of heat by molecular motion) we have convection, by which the heat is carried off by the general upward flow of the gas.

With an infinitely small radiator each molecule comes in contact with the radiator at the temperature of the enclosure. With a radiator ot large area a certain proportion of the molecules which strike its upper surface have already become heated by previous contact. The heat lost by convection decreases therefore as the diameter of the radiator increases; it is obvious, however, that it can never become zero, but must tend towards a constant quantity.

Such experimental observations as are available point to the same conclusion, the loss by convection being best represented by an expression of the form $c_2 + c_3 r^{-1}$. The loss by radiation is independent of the size of the radiator and may be put equal to a constant, c_4. The variation of emissivity with the size of the radiator is therefore expressed by the following formula :—

$$\text{Emissivity} = c_2 + c_4 + (c_1 + c_3) r^{-1} = \text{C} + \text{C}' r^{-1} \quad . \quad . \quad . \quad . \quad \text{(vi.)}.$$

This is the same expression as was established empirically by AYRTON and KILGOUR.* Within the range of their experiments ($r = 0{\cdot}0157$ to $r = 0{\cdot}178$ millim.) both C and C′ were constants.

In an investigation on the effect of the size of the enclosure, formula (iii.) is not suitable. It was established that the length of the cylinder was sufficiently great in comparison with its diameter to render the end effects negligible. We therefore cannot put $\text{R} = \infty$. If, however, we take the simple case of a spherical enclosure and radiator, and reason by analogy, we can easily obtain the information we desire.

Proceeding as on page 240, the thermal resistance of the elementary spherical shell is

$$\frac{1}{4\Pi\text{K}} \times \frac{dr}{r^2}.$$

Integrating we get for the total resistance

$$\frac{1}{4\Pi\text{K}}\left(\frac{1}{r} - \frac{1}{\text{R}}\right) = \frac{1}{4\Pi\text{K}} \times \frac{\text{R} - r}{\text{R}r}.$$

The part of the emissivity due to conduction is therefore

$$\text{E}_c = \frac{\text{K}}{r} \times \frac{\text{R}}{\text{R} - r}.$$

---

* AYRTON and KILGOUR ('Phil. Trans.,' A, vol. 183, p. 371, 1892) have shown that an expression of this form holds good for the smallest diameters that can practically be used. It would, however, be unwise to extend the formula much beyond the limit within which it has been experimentally proved. It is evident that for $r = 0$ the expression is at fault, for the value of the emissivity cannot exceed $\text{E} = \text{NC}$ where N is the number of molecular impacts and C the molecular specific heat.

If R/r is made very great E_c is nearly constant with regard to R and is equal to K/r, showing that if the enclosure is above a given size, the heat lost by conduction is practically independent of its actual dimensions.

The theoretical treatment of the variations of the emissivity with the temperatures of the gas offers some difficulties.

On the one hand the conductivity increases in proportion to the viscosity, on the other the convection is a function of the density divided by the viscosity. Taking the gas at the same density, both at the high and the low temperature, we may safely predict that at low pressures, where the effect of conductivity predominates, a rise in temperature will correspond to an increased value of the emissivity. At high pressures, however, with the data at present available, a theoretical solution is not possible.

The results of two sets of experiments made with carbon dioxide are given below—

Emissivity in Carbon Dioxide in C.G.S. Units.

Temperature* ϑ in degrees Centigrade.	Pressure 19·9 atmospheres at 16° C.		Pressure 45·5 atmospheres at 16° C.	
	Enclosure at 18° C.	Enclosure at 100° C.	Enclosure at 18° C.	Enclosure at 100° C.
200	0·0032	0·0032	0·0058	0·0053
300	0·0036	0·0038	0·0063	0·0058
400	0·0040	0·0044	0·0068	0·0063
500	0·0044	0·0048	0·0074	0·0068
600	0·0048	0·0053	0·0079	0·0075
700	0·0052	0·0057	0·0084	0·0081

We see that even at 20 atmospheres an increase of 34 per cent. in the absolute temperature causes an increase of about 10 per cent. in the value of the emissivity.

In the case of carbon dioxide, and probably of all easily condensible gases, when the pressure is near that which would bring about a change of state, the emissivity is diminished by a rise of temperature.

Finally the question of the average temperature of the gas in the enclosure in its relation to that of the radiator offers some interest. It can be determined from the variation of pressure, for the apparatus constitutes a rough form of constant volume thermometer. On the other hand, when the heat lost by convection is small, the average temperature can be calculated from the equations on page 240.

If we divide the gas into a series of concentric cylinders, the boundaries of these cylinders will be isothermal surfaces, and the fall of temperature from the inner to

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* ϑ = temperature of the radiator − temperature of the enclosure in degrees Centigrade.

the outer surface of each cylinder will be proportional to the thermal resistance. By plotting the temperatures in terms of the volume of the successive cylinders, integrating the curve and dividing by the total volume, we obtain the average temperature of the gas. This works out as 15 per cent. of the temperature of the radiator if we take the temperature of the enclosure as the zero of our scale.

The same ratio experimentally determined is about 6 per cent. This relatively low value is accounted for by the fact that each gaseous particle does not only part with its heat to the succeeding one, but streaming upwards, comes sooner or later in contact with the upper wall of the enclosure.

A Numerical Comparison of the Heat dissipated by Conductivity in Solids and by Emissivity in Gases.

Let us now consider the numerical values of the total emissivity obtained at high pressures. At 160 atmospheres, for instance, in air the emissivity is (see formula (ii.))

$$E = 0{\cdot}006912 + 0{\cdot}000004732\,\vartheta.$$

Thus at 160 atmospheres air dissipates heat at the same rate as a body having a conductivity

$$K = 0{\cdot}0011\,(1 + 0{\cdot}00069\,\vartheta),$$

therefore at about the same rate as glass ($K = 0{\cdot}001$) or plaster of Paris ($K = 0{\cdot}0013$).

The conductivity of water is about the same—

$$K = 0{\cdot}0012\,(1 - \alpha\vartheta),$$

but in this case the comparison is not a fair one, for placed in similar circumstances convection would also come into play, causing the total loss of heat to be much greater.

Hydrogen at 120 atmospheres behaves like a body having a conductivity

$$K = 0{\cdot}00237\,(1 - 0{\cdot}00072\,\vartheta).$$

Finally the emissivity in liquid carbon dioxide is about 0·2, which would correspond to a conductivity of 0·03, therefore higher than mercury or bismuth. The conductivity in liquid nitrous oxide is nearly the same. Near the critical temperature the emissivity in the liquids rises very rapidly ; it falls again instantaneously to less than one-tenth of its former value when the gaseous state is reached.

A point of some interest which was observed during the course of the work was the gradual change in the phenomenon of the decomposition of nitrous oxide. At a pressure of 1 atmosphere the decomposition was very slow and more than half an hour had elapsed before the change was anything like complete.

At increasing pressures the decomposition became more rapid, and finally, in an experiment in which the apparatus had, at the start, been partially filled with liquid gas, it took the form of a sharp explosion. The temperature of decomposition is for all pressures about the same, and lies between 800 and 900 degrees Centigrade.

Some measurements taken in liquid nitrous oxide and liquid carbon dioxide are given in Table VII. (p. 251).

Conclusions.

The general result of the investigation is to show that the law which connects the thermal emissivity with the temperature of the radiator and the pressure of the gas is—

$$E = ap^{\alpha} + bp^{\beta}\vartheta,$$

where E = Emissivity = Heat dissipated per second, per degree Centigrade temperature interval, per centimetre of area, expressed in gramme-degrees. a, α, b, β, are the constants given on page 236, p is the pressure in atmospheres, and ϑ the temperature interval.

The bearing on astro-physical problems is at once apparent, and the high effective conductivity of compressed gases must be taken into account when treating questions relative to the mean temperature of the sun, its rate of cooling, or more generally, any problem dealing with the physical state of gaseous astral bodies.

Although extrapolations are always very uncertain, in the present case it seems justifiable to conclude that under the very great pressures with which astronomical physics has to deal, all gases or vapours would transmit heat at a higher rate than the best conducting solids known.

From a practical point of view, the results obtained explain the very rapid cooling of the products of an explosion, a fact which has not only been noticed during the course of experiments on ballistics, but has long been well known to all engineers engaged in the construction of gas engines.

The relatively small cooling surface required, in the case of gases under high pressures, is a fact that had been previously noticed, and is already to some extent taken account of in the design of the modern compressors.

The laws of thermo-dynamics show that the efficiency of all heat engines is dependent on their temperature range and pressure: in compliance with these laws the pressures used are daily becoming greater. It is therefore hoped that the present investigation may be of some use to those engaged in practical engineering.

Before closing, I desire to express my indebtedness to Dr. LUDWIG MOND, the donor of the Davy-Faraday Laboratory, at which Institution the greater part of the work was carried out. My sincere thanks are also due to Dr. ALEXANDER SCOTT for the kind way in which he has facilitated the research by every means in his power.

Table II.—Emissivity in Air.

0·113 atmosphere at 16° C.		0·969 atmosphere at 16° C.		7·08 atmospheres at 16° C.		20·92 atmospheres at 16° C.	
Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.
118·5	0·0005545	82·1	0·0007505	98·2	0·001522	65·9	0·002205
296·7	0·0007021	199·0	0·0009533	308·0	0·002084	204·3	0·002886
466·8	0·0008680	355·4	0·001139	656·5	0·002801	422·8	0·003529
771·9	0·001325	635·8	0·001518	802·5	0·003385	735·2	0·004468
962·6	0·001784	865·9	0·001957	945·0	0·003605	899·6	0·004975
		966·0	0·002213			1060·2	0·005673

39·3 atmospheres at 16° C.		65·4 atmospheres at 16° C.		124·7 atmospheres at 16° C.		168·4 atmospheres at 16° C.	
Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.
165·1	0·003724	114·3	0·004792	88·1	0·005869	82·5	0·007198
378·1	0·004544	283·2	0·005433	199·3	0·006785	150·0	0·007909
571·5	0·005191	463·5	0·006086	303·2	0·007453	258·3	0·008573
771·0	0·005856	621·7	0·006635	503·7	0·008386	418·8	0·009496
902·5	0·006363	872·6	0·007670	689·1	0·009113	567·1	0·01012
1006·7	0·006809	1055·3	0·008485	926·9	0·01022	787·5	0·01116
						915·5	0·01175
						1031·1	0·01242

Table III.—Emissivity in Oxygen.

0·086 atmosphere at 16° C.		1·01 atmospheres at 16° C.		10·0 atmospheres at 16° C.	
Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.
86·5	0·000513	222·7	0·001080	256·4	0·002349
288·1	0·000683	571·7	0·001515	483·0	0·002946
381·1	0·000793	921·9	0·002231	733·3	0·003557
585·0	0·001066			976·9	0·004280
736·3	0·001352				
922·6	0·001869				

TABLE I.—Emissi

I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.
		Current reversed.									
ctro- tive ce in lts.	Current in amperes.	Electromotive force in volts.	Current in amperes.	Mean electromotive force.	Mean current.	Power dissipated in watts.	Resistance of radiator in ohms.	$(R - R_0)$ where R = actual resistance R_0 = resistance at 0° C.	Temperature of radiator in platinum degrees.	Temperature of radiator in Centigrade degrees.	Tempera ture of enclosur in Fahren heit degrees.
fore t	he electri	c current	was start	ed	—	—	—	—	—	—	59·5
3800	22·36	0·3816	22·39	0·3808	22·38	8·522	0·01701	0·00684	179·0	181·2	61·0
7615	31·02	0·7693	31·20	0·7654	31·11	23·81	0·02460	0·01443	377·6	395·0	62·5
122	36·32	1·137	36·45	1·130	36·39	41·11	0·03105	0·02088	546·3	589·5	64·5
523	40·85	1·530	41·10	1·527	40·98	62·57	0·03726	0·02709	708·7	790·4	67·0
800	43·93	1·818	44·07	1·809	44·00	79·60	0·04111	0·03094	809·5	923·1	69·0
035	46·40	2·055	46·52	2·045	46·46	95·01	0·04402	0·03385	885·7	1028·4	71·0
n min	utes after	the electr	ic current	was stop	ped	—	—	—	—	—	59·0

---

* For each column in the following tables a similar set of observations were taken and worked out in the manner s

† The emissivity is numerically equal to the heat dissipated per sq. centim. of surface of the radiator pe

Current in amperes. S = surface of radiator.

electromotive force in volts. $\vartheta = t_r - t_e$ = temperature of radiator − temperature of enclosure.

The diameter of the

The length between

The superficial area

The resistance of

Therefore the tem

The fundam

Where R_1 = resista

In the formula $(t - Pt)$ =

The temperature of the CLARK'S

sivity in Air at 39·3 Atmospheres (16° C.).*

.	XIII.	XIV.	XV.	XVI.	XVII.	XVIII.	XIX.	XX.	XXI.	XXII.	XX
era- of ure en- es.	Temperature of enclosure in Centigrade degrees.	Temperature difference $\vartheta = (t_r - t_e)$ where t_r = temp. of radiator, t_e = temp. of enclosure.	Power dissipated in watts per degree Centigrade.	Emissivity† in C.G.S. units.	Temperature of water circulation at exit.	Temperature of pressure gauge.	Zero of pressure gauge.	Pressure gauge reading.	P_1V_1 where V_1 = original volume P_1 = original pressure at temperature given in column XVIII.	V_2 volume calculated from column XX.	P_2 = cul pres
5	15·3	—	—	—	15·8	18·3	44·72	45·40	77·03	1·97	39
0	16·1	165·1	0·05162	0·003724	16·2	—	44·72	45·41	77·08	1·96	39
5	16·9	378·1	0·06298	0·004544	16·4	—	44·84	45·85	77·13	1·89	40
5	18·0	571·5	0·07195	0·005191	16·8	—	,,	45·95	77·19	1·87	41
0	19·4	771·0	0·08116	0·005856	17·2	—	,,	46·10	77·24	1·83	42
0	20·6	902·5	0·08819	0·006363	17·9	—	44·83	46·18	77·29	1·82	42
0	21·7	1006·7	0·09438	0·006809	18·2	—	,,	46·28	77·34	1·80	42
0	15·0	—	—	—	15·7	19·7	,,	45·3	77·40	1·99	38

shown above, but to save space and avoid confusion the final results are alone recorded.

er second per degree Centigrade temperature interval, the heat being expressed in water-gramme-degrees (t

Observations.

ne bright platinum radiating wire was 1·106 millims.

n potential contacts . . . . . 9·498 centims.

a . . . . 3·300 sq. centims.

of the radiator was at 100° C. = 0·013987

at 0° C. = 0·010165

mperature coefficient $\frac{R_1 - R_0}{100} = 0 \cdot 00003822$

$$\frac{R_1}{R_0} = 1 \cdot 3759$$

amental coefficient $= \frac{R_1 - R_0}{100 R_1} = 0 \cdot 003760$

tance at 100° C.; R_0 = resistance at 0° C.

$= \delta \left[\left(\frac{t}{100}\right)^2 - \frac{t}{100}\right]$ the coefficient δ was $\delta = 1 \cdot 495$.

s cell was 17·3; it was balanced at 1·4317 on the potentiometer.

Petavel, Table I.

XII.	XXIII.	XXIV.	XXV.	XXVI.
$_2$ ume al- ated om umn X.	P_2 P_2 = calculated pressure.	P_2 corrected for the weight of mercury column.	Pressure P_2 corrected for the departure of air from Boyle's law.	Temperature of standard resistance.
97	39·10	39·85	39·26	17·3
96	39·33	40·08	39·48	—
89	40·81	41·56	40·92	—
87	41·28	42·03	41·38	19·0
83	42·20	42·95	42·27	—
82	42·47	43·23	42·55	20·1
80	42·97	43·73	43·04	—
99	38·90	39·64	39·06	18·3

egrees (therms) or $E = \frac{V \times A}{JS\vartheta}$, where

TABLE III.—Emissivity in Oxygen (*continued*).

37·8 atmospheres at 16° C.		71·6 atmospheres at 16° C.		115·9 atmospheres at 16° C.	
Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.
182·5	0·003777	132·1	0·004877	96·2	0·006370
395·9	0·004660	244·9	0·005631	194·6	0·007100
563·8	0·005315	429·2	0·006512	337·7	0·008124
845·1	0·006329	639·3	0·007403	462·0	0·008687
1075·8	0·007450	820·4	0·008218	638·0	0·009452
		1091·4	0·009561	867·0	0·01056
				1064·2	0·01176

TABLE IV.—Emissivity in Hydrogen.

0·117 atmosphere at 16° C.		0·971 atmosphere at 16° C.		6·9 atmospheres at 16° C.	
Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.
189·8	0·003062	168·8	0·003476	141·8	0·004899
523·8	0·004158	508·9	0·004920	229·8	0·006100
681·1	0·005098	692·5	0·005818	644·7	0·008038
690·1	0·005032	929·9	0·006675	834·2	0·008738
775·7	0·005372	989·4	0·007288	952·2	0·009417
903·7	0·005854	619·8	0·005150	450·2	0·007425
		367·3	0·004180	233·3	0·006030
		268·7	0·003762		
		162·2	0·003365		

23·3 atmospheres at 16° C.		66·9 atmospheres at 16° C.		114·0 atmospheres at 16° C.	
Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.
82·5	0·007380	136·1	0·01203	161·1	0·01533
143·9	0·008369	257·8	0·01396	404·7	0·01920
355·6	0·01032	402·1	0·01554	620·4	0·02135
594·1	0·01194	521·6	0·01670	791·1	0·02268
740·0	0·01278	669·8	0·01816	950·9	0·02454
941·4	0·01405			275·8	0·01742
79·8	0·007338			165·8	0·01558
287·9	0·009841			89·8	0·01350
508·1	0·01149				

TABLE V.—Emissivity in Carbon Dioxide.

0·07 atmosphere at 16° C.		0·99 atmosphere at 16° C.		4·4 atmospheres at 16° C.		10·2 atmospheres at 16° C.	
Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.S.G. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.
167·6	0·0004537	187·9	0·0008695	387·3	0·002037	79·7	0·001619
340·0	0·0006094	403·7	0·001176	732·3	0·002911	173·5	0 001997
662·5	0·001018	804·5	0·001893	979·5	0·003666	441·3	0·002853
847·5	0·001410	1063·0	0·002509	156·0	0·001335	684·2	0·003588
						919·3	0·004310
992·1	0·001780	247·0	0·0009439				
		602·2	0·001527				
		835·9	0·002005				

18·1 atmospheres at 16° C.		34·8 atmospheres at 16° C.		54·0 atmospheres at 21°·1 C.	
Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.
197·4	0·003102	88·1	0·004127	68·7	0·007002
341·0	0·003752	265·8	0·005157	167·4	0·007215
554·2	0·004576	480·5	0·006132	337·4	0·007618
764·5	0·005306	671·2	0·007038	595·8	0·008414
964·7	0·006130	950·1	0·008066	901·4	0·009339
		835·2	0·007670		

Table VI.—Emissivity in Nitrous Oxide.

0·93 atmosphere at 16° C.		5·66 atmospheres at 16° C.		14·48 atmospheres at 16° C.		39·0 atmospheres at 16° C.	
Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.
60·8	0·000647	90·6	0·001292	78·5	0·001962	124·8	0·004687
192·8	0·000898	289·7	0·001922	263·0	0·002835	207·9	0·005161
341·4	0·001126	642·0	0·002842	418·4	0·003378	337·6	0·005782
585·6	0·001546	1138·9	0·004296	605·1	0·004006	576·4	0·006839
799·2	0·002003			844·5	0·004967	732·2	0·007383
1066·5	0·002773			1093·3	0·005653	807·3	0·007796
						1080·8	0·008325
						115·3	0·004712
						264·2	0·005498
						485·9	0·006505

Table VII.

Emissivity in liquid carbon dioxide.		Emissivity in liquid nitrous oxide.	
Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.	Temperature ϑ in degrees Centigrade.	Emissivity in C.G.S. units.
5·9	0·27*	7·4	0·11*
7·0	0·27*	9·7	0·12*
	gas.		
176·7	0·016	10·5	0·15*
84·8	0·018	11·1	0·20*
98·8	0·017	11·4	0·26*
308·1	0·016		gas.
463·9	0·016	308·5	0·015

* These measurements are only given as preliminary and altogether approximate values; as already stated, the apparatus is not suitable for measurements depending on small temperature intervals.

TABLE VIII.—Emissivity in Air.

$$E \times 10^6 = 403\,p^{0{\cdot}56} + 1{\cdot}63\,p^{0{\cdot}21}\,\vartheta.$$

ϑ = temp. of radiator above the enclosure in degrees Centigrade.	0·1* atmosphere.	1·0* atmosphere.	10 atmospheres.	20 atmospheres.	30 atmospheres.	40 atmospheres.	50 atmospheres.	60 atmospheres.
100	*0·00050*	*0·00084*	0·001728	0·002463	0·003040	0·003534	0·003974	0·004376
200	*0·00060*	*0·00095*	0·001992	0·002769	0·003373	0·003888	0·004345	0·004761
300	*0·00070*	*0·00106*	0·002256	0·003074	0·003706	0·004241	0·004715	0·005146
400	*0·00078*	*0·00119*	0·002520	0·003380	0·004039	0·004595	0·005086	0·005531
500	*0·00086*	*0·00132*	0·002785	0·003686	0·004372	0·004949	0·005457	0·005916
600	*0·00098*	*0·00148*	0·003049	0·003992	0·004705	0·005202	0·005827	0·006302
700	*0·00114*	*0·00165*	0·003314	0·004298	0·005038	0·005656	0·006198	0·006687
800	*0·00135*	*0·00182*	0·003578	0·004603	0·005371	0·006010	0·006569	0·007072
900	*0·00157*	*0·00205*	0·003842	0·004909	0·005704	0·006363	0·006939	0·007457
1000	*0·00180*	*0·00232*	0·004107	0·005215	0·006037	0·006717	0·007310	0·007842
1100	—	—	0·004371	0·005511	0·006370	0·007071	0·007681	0·008227
1200	—	—	0·001636	0·005827	0·006702	0·007424	0·008051	0·008612

ϑ = temp. of radiator above the enclosure in degrees Centigrade.	80 atmospheres.	100 atmospheres.	120 atmospheres.	140 atmospheres.	160 atmospheres.	Temp. of radiator in degrees Centigrade above the temperature of the enclosure.	Heat lost by convection = E_c calculated, taking $K_0 = 0{\cdot}0000561$, $\alpha = 0{\cdot}0019$, and $E_c = 6{\cdot}184 \times K$.	Radiation according to J. T. BOTTOMLEY's results.	Loss of heat due to conduction + radiation.
100	0·005098	0·005741	0·006329	0·006874	0·007385	100	0·000413	0·000034	0·000447
200	0·005507	0·006170	0·006775	0·007334	0·007859	200	0·000479	0·000059	0·000538
300	0·005916	0·006599	0·007220	0·007795	0·008332	300	0·000545	0·000094	0·000639
400	0·006325	0·007028	0·007666	0·008255	0·008805	400	0·000611	0·000134	0·000745
500	0·006734	0·007456	0·008111	0·008715	0·009278	500	0·000677	0·000176	0·000853
600	0·007143	0·007885	0·008556	0·009175	0·009751	600	0·000742	0·000218	0·000960
700	0·007552	0·008314	0·009002	0·009635	0·010225	700	0·000808	0·000259	0·001067
800	0·007961	0·008743	0·009447	0·010095	0·010698	800			
900	0·008371	0·009171	0·009893	0·010555	0·011170	900			
1000	0·008780	0·009600	0·010338	0·011016	0·011643	1000			
1100	0·009189	0·0100[illegible]9	0·010784	0·011475	0·012117	1100			
1200	0·009598	0·010457	0·011229	0·011936	0·012590	1200			

* In this and the four following tables the figures in italics, referring to pressures outside the range of the formulæ, are obtained from a direct interpolation of the observed values. In every case the emissivity is expressed in water-gramme-degrees per square centimetre of radiating surface per second.

TABLE IX.—Emissivity in Oxygen.

$$E \times 10^6 = 387\, p^{0\cdot58} + 1\cdot39\, p^{0\cdot28}\, \vartheta.$$

Temperature ϑ in degrees Centigrade.	0·10 atmosphere.	1·0 atmosphere.	10 atmospheres.	30 atmospheres.	50 atmospheres.	80 atmospheres.	100 atmospheres.	120 atmospheres.
100	*0·00052*	*0·00095*	0·001735	0·003142	0·004158	0·005425	0·006099	0·006749
300	*0·00072*	*0·00118*	0·002265	0·003863	0·004988	0·006337	0·007108	0·007811
500	*0·00097*	*0·00143*	0·002796	0·004583	0·005821	0·007285	0·008118	0·008874
700	*0·00126*	*0·00168*	0·003225	0·005304	0·006652	0·008234	0·009127	0·009936
900	*0·00179*	*0·00215*	0·003855	0·006025	0·007483	0·009182	0·010136	0·010998
1100	—	—	0·004385	0·006745	0·008315	0·010130	0·011146	0·012052

TABLE X.—Emissivity in Hydrogen.

$$E \times 10^6 = 2750\, p^{0\cdot35} + 1\cdot88\, p^{0\cdot36}\, \vartheta.$$

Temperature ϑ in degrees Centigrade.	0·10 atmosphere.	1·0 atmosphere.	10 atmospheres.	30 atmospheres.	50 atmospheres.	80 atmospheres.	100 atmospheres.	120 atmospheres.
100	*0·00285*	*0·00314*	*0·00520*	*0·00830*	*0·01000*	*0·01195*	*0·01310*	*0·01416*
300	*0·00342*	*0·00394*	0·00745	0·01096	0·01312	0·01548	0·01674	0·01785
500	*0·00413*	*0·00486*	0·00831	0·01224	0·01466	0·01730	0·01872	0·01996
700	*0·00498*	*0·00577*	0·00917	0·01352	0·01619	0·01912	0·02069	0·02207
900	*0·00586*	*0·00667*	0·01003	0·01480	0·01773	0·02094	4·02266	0·02417
1100	*0·00673*	*0·00757*	0·01089	0·01608	0·01927	0·02276	0·02464	0·02628

TABLE XI.—Emissivity in Carbon Dioxide.

$$E \times 10^6 = 207\,p^{0\cdot 82} + 1\cdot 5\,p^{0\cdot 33}\vartheta.$$

Temperature ϑ in degrees Centigrade.	0·1 atmosphere.	1·0 atmosphere.	10 atmospheres.	30 atmospheres.	50 atmospheres.
100	*0·00044*	*0·00074*	0·001688	0·003828	*0·00675*
300	*0·00060*	*0·00103*	0·002330	0·004749	*0·00735*
500	*0·00079*	*0·00134*	0·002971	0·005671	*0·00792*
700	*0·00110*	*0·00172*	0·003613	0·006593	*0·00852*
900	*0·00155*	*0·00210*	0·004254	0·007515	*0·00912*
1100	*0·00210*	*0·00260*	0·004895	0·008436	*0·00975*

TABLE XII.—Emissivity in Nitrous Oxide.

$$E \times 10^6 = 276\,p^{0\cdot 74} + 1\cdot 7\,p^{0\cdot 28}\vartheta.$$

Temperature ϑ in degrees Centigrade.	1·0 atmosphere.	10 atmospheres.	30 atmospheres.
100	*0·00070*	0·001841	0·003860
300	*0·00105*	0·002488	0·004741
500	*0·00140*	0·003136	0·005623
700	*0·00172*	0·003784	0·006504

TABLE I.—Emissivity in Air at 50·3 Atmospheres (16° C.).*

I.	II.	III.	IV.	V.	VI.	VII.	VIII.	IX.	X.	XI.	XII.	XIII.	XIV.	XV.	XVI.	XVII.	XVIII.	XIX.	XX.	XXI.	XXII.	XXIII.	XXIV.	XXV.	XXVI.
ectromo-tive ce in lts.	Current in amperes.	Current reversed.		Mean electromotive force.	Mean current.	Power dissipated in watts.	Resistance of radiator in ohms.	$(R - R_0)$ where R = actual resistance R_0 = resistance at 0° C.	Temperature of radiator in platinum degrees.	Temperature of radiator in Centigrade degrees.	Temperature of enclosure in Fahrenheit degrees.	Temperature of enclosure in Centigrade degrees.	Temperature difference $\theta = (t_r - t_e)$ where t_r = temp. of radiator, t_e = temp. of enclosure.	Power dissipated in watts per degree Centigrade.	Emissivity† in C.G.S. units.	Temperature of water circulation at exit.	Temperature of pressure gauge.	Zero of pressure gauge.	Pressure gauge reading.	P_1V_1 where V_1 = original volume P_1 = original pressure at temperature given in column XVIII.	V_2 volume calculated from column XX.	P_2 P_2 = calculated pressure.	P_2 corrected for the weight of mercury column.	Pressure P_2 corrected for the departure of air from Boyle's law.	Temperature of standard resistance.
		Electromotive force in volts.	Current in amperes.																						
fore the electric current was started					—	—		...	—	—	59·5	15·3	—	...	...	15·8	18·5	44·72	45·10	77·09	1·97	39·10	39·85	39·20	17·3
3800	22·36	0·3816	22·39	0·3808	22·38	8·522	0·01701	0·00684	179·0	181·2	61·0	16·1	165·1	0·05162	0·003724	16·2	—	44·72	45·41	77·08	1·96	39·33	40·08	39·48	...
7615	31·02	0·7693	31·20	0·7654	31·11	23·81	0·02460	0·01445	377·0	395·0	62·5	16·9	378·1	0·06298	0·004544	16·4	– –	44·84	45·55	77·13	1·89	40·81	41·56	40·92	
123	36·32	1·137	36·45	1·130	36·39	41·11	0·03105	0·02088	546·3	588·5	64·5	18·0	570·5	0·07195	0·005191	16·8		,,	45·95	77·19	1·87	41·28	42·08	41·38	19·0
520	40·83	1·530	41·13	1·525	40·98	62·57	0·03724	0·02706	706·7	790·4	67·0	19·4	771·0	0·08115	0·005856	17·2	...	,,	46·10	77·24	1·83	42·20	42·95	42·27	—
800	43·93	1·818	44·07	1·809	44·00	79·60	0·04111	0·03091	809·5	953·1	69·0	20·6	932·5	0·08819	0·006363	17·9	—	44·88	46·15	77·30	1·82	42·47	43·23	42·55	20·1
035	46·40	2·055	46·52	2·045	46·46	95·01	0·04402	0·03385	885·7	1028·4	71·0	21·7	1006·7	0·09438	0·006800	18·2	—	,,	46·26	77·31	1·80	42·97	43·73	43·04	·
n minutes after the electric current was stopped							—	—	---		59·0	15·0				15·7	20·7	,,	45·9	77·15	1·98	38·90	39·64	39·06	18·3

* For each column in the following tables a similar set of observations were taken and worked out in the manner shown above, but to save space and avoid confusion the final results are alone recorded.

† The emissivity is numerically equal to the heat dissipated per sq. centim. of surface of the radiator per second per degree Centigrade temperature interval, the heat being expressed in water-gramme-degrees (therms) or $E = \frac{V \times A}{JS\theta}$, where

Current in amperes. S = surface of radiator.

electromotive force in volts. $\theta = t_r - t_e$ = temperature of radiator − temperature of enclosure.

Observations.

The diameter of the bright platinum radiating wire was 1·108 millims.

The length between potential contacts . . . . . . 9·495 centims.

The superficial area . . . . 3·300 sq. centims.

The resistance of the radiator was at 100° C. = 0·013887

at 0° C. = 0·010185

Therefore the temperature coefficient $\frac{R_1 - R_0}{100} = 0·00003822$

$\frac{R_1}{R_0} = 1·3709$

The fundamental coefficient $= \frac{R_1 - R_0}{100R_1} = 0·003760$

Where R_1 = resistance at 100° C.; R_0 = resistance at 0° C.

In the formula $(t - Pt) = \delta\left[\left(\frac{t}{100}\right)^2 - \frac{t}{100}\right]$ the coefficient δ was $\delta = 1·495$.

The temperature of the CLARK's cell was 17·3; it was balanced at 1·4317 on the potentiometer.