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But there are one or two experiments that might be suggested that could be very easily performed without any special expensive or complicated apparatus. Thus it would be very interesting to keep an iron plate red hot in a stream of pure dry hydrogen for several hours, allow it to cool in that gas, leaving it say for a few days, and then measure the contact P.D. between it and another iron plate that had not been so treated. This might be repeated with a platinum plate, and the two experiments together would then be somewhat equivalent to those described on pp. 85-87, and very much simpler to perform.

§ 17. It is with the hope that somebody will find it worth while to continue investigations along these lines, that I venture to publish these preliminary results*.

Throughout the whole of this work I have been fortunate enough to receive the valued assistance and advice of Prof. W. E. Ayrton, F.R.S., in whose laboratories at the Central Technical College the work was done, and of Mr. T. Mather, his Senior Demonstrator in the Physical Department. I must also thank my friend Mr. W. Duddell and Mr. W. T. Evans, who have so often kindly helped me, when necessary, in the experimental part of the work.

V. *On the Expansion of Porcelain with Rise of Temperature.*
By T. G. BEDFORD, B.A., *Sidney Sussex College, Cambridge*†.

IN experiments involving the use of air-thermometers, such as comparisons between the air and platinum-resistance scales of temperature, a correction is required for the expansion of the thermometric envelope. Over a range at low temperatures the expansion might be readily determined, *e. g.*, by filling the bulb with a liquid, conveniently mercury, whose absolute expansion is known, and using it as a weight-thermometer to measure the relative expansion of the liquid. At high temperatures, however, such a method cannot well be used, and the correction must be calculated either from the results of low temperature measurements, or from the linear expansion as determined directly at these higher temperatures, provided the material be homogeneous. As porcelain is the substance generally used, this latter method is available; and it was therefore suggested to me by Mr. E. H. Griffiths, F.R.S., that it might be useful to try

* Since the above was written I am very pleased to be able to add that Mr. H. Tomlinson has now taken up the thread of this research, working, for the present, with my old apparatus, and starting from the point at which I left off.

† Communicated by the Physical Society.

to determine how the expansion of porcelain varies with the temperature.

Direct determinations of the linear expansion of porcelain have been made by Deville and Troost (*Comptes Rendus*, lix. p. 162, 1864), and by Holborn and Wien (*Ann. Phys. Chem.* xlvii. p. 107, 1892). In the experiments of Deville and Troost on Bayeux porcelain the temperatures were measured by means of an air-thermometer heated in the same enclosure with the experimental rod, and having its bulb of the same kind of porcelain. Readings were taken at 0° C. and again at temperatures between 1000° and 1500°. The conclusion reached was that the coefficient of cubical expansion is constant, and between .000016 and .000017. In the experiments of Holborn and Wien the expansion of a length of 9 cm. of Berlin porcelain was measured, the temperature being determined by a thermo-electric junction in contact with the porcelain. Measurements were taken at the temperature of the room, and again at about 1000° in some experiments, at about 500° in others. As the values found for the mean coefficient for one of these intervals agreed as well with those found for the other interval as they did amongst themselves, these experimenters also concluded that the coefficient is constant. The mean value of the coefficient of linear expansion for the kind of porcelain used for their air-thermometers is taken as .0000044.

The method adopted in the experiments described in the present paper was essentially the same as that employed in the case of *glass* by Callendar (*Phil. Trans.* 1887 A, p. 167), and by Callendar and Griffiths (*Phil. Trans.* 1891 A, p. 123).

A tube of glazed Bayeux porcelain about 1 metre long and 1.7 cm. external diameter was used. Two fine transverse scratches ran round the tube at a distance of about 91 cm. from each other; and the distance between these marks was directly compared at a series of temperatures from 0° C. to 830° C. with a standard length, by means of a pair of reading microscopes.

The mean temperature of the portion of the tube between the marks was deduced from the resistance of a platinum wire (doubled for the sake of obtaining a convenient value for $R_{100} - R_0$) which passed straight down the tube from one mark to the other and back again. The wire was fastened down at intervals to a strip of mica which fitted the tube fairly tightly. At the upper mark the wires were attached to others of thicker platinum, which were themselves joined at the pyrometer-head which closed this end of the tube to

copper leads. The head also carried a second pair of terminals to which was attached a thick platinum wire running to the upper mark and back to act as a "compensator."

Connexion was made between the pyrometer-head and the resistance-box by means of a carefully equalized and insulated fourfold cable. The lower end of the porcelain tube was closed by a porcelain plug.

The resistance measurements were made by the usual Wheatstone-bridge method, the arms of the bridge being equal. The resistance-box used contains a set of 7 coils of nominal values 10 to 640 mean box-units, and in series with the coils a bridge-wire 40 cm. long, the effective resistance of 1 cm. of which is equal approximately to 1 box-unit. By means of a vernier $\cdot 01$ cm. can be read. The mean box-unit is roughly $\cdot 01$ ohm*. A careful standardization of both coils and bridge-wire was made in January 1898, by Mr. E. H. Griffiths and Mr. C. F. Green; and again in May 1899, since the completion of these experiments, the coils have been restandardized by Mr. C. F. Green, and show no perceptible change since the previous standardization. The resistance of the pyrometer-wire was about 260 box-units at 0° C. The current from a dry cell through 20 ohms was employed, and was found to produce no serious heating-effect. Thermo-electric effects were eliminated by the use of Griffiths' Thermo-electric key (Phil. Trans. 1893 A, p. 398). A dead-beat mirror galvanometer was used.

The reading-microscopes, for the use of which the writer is indebted to Prof. Ewing, were made by the Cambridge Scientific Instrument Company. They were supported on solid stone blocks standing on a firm stone bench. The microscope-carriage moves along its slides by means of a screw of $\cdot 5$ mm. pitch, the head being divided into 100 parts and thus reading to $\cdot 005$ mm. Tenths of these divisions could be estimated, but the diamond marks on the porcelain were not sufficiently good to enable settings of the cross-wire to be made to such accuracy. The gas furnace in which the tube was heated was supported on a stand provided with levelling screws, by adjusting which the marks were kept in focus as the tube was heated or cooled. Both the microscopes and bench were screened by bright tinned plate from the radiation from the furnace. As a standard length the distance between two diamond marks on a glass tube kept in a trough of melting ice was used. This distance was equal to $91\cdot 394$ cm. During each experiment the readings for the glass tube were taken at intervals.

* There is a full description of a box of this type, known as the "Student's Box," in the 'Electrical Review,' Aug. 18, 1899.

For the determination of the fixed points R_0 and R_{100} , the apparatus was more cumbersome than that used for smaller pyrometers. In determining R_{100} , steam from a boiler was led into a metal tube about 6 cm. in diameter surrounding the porcelain tube. The metal tube was surrounded by a similar wider tube 10 cm. in diameter and co-axial with it. The steam, passing along the inner metal tube, returned through the space between the two tubes, forming a jacket, and thence passed out to a condenser. A siphon-gauge showed any excess of steam-pressure within the apparatus above the atmospheric pressure. The jacketed steam vessel and the tubes leading from the boiler were carefully packed round with cotton-wool and hair felt. The steam-vessel was slightly inclined to the horizontal, so that the condensed water might drain away. It was found that with this arrangement the readings very soon became steady when steam was passed into the apparatus; and the values of R_{100} deduced from experiments on different days and under different barometric pressures agreed satisfactorily with one another.

The ice-point R_0 was determined by immersing the porcelain tube in a mixture of pounded ice and water contained in a vessel formed from the larger of the metal tubes used for the steam-point determinations.

The sample of platinum wire, from which the piece used in these experiments was cut, is known to have a value of δ , in Callendar's formula, from 1.50 to 1.51. The value $\delta = 1.505$ was assumed, and thus a direct determination of the resistance at the temperature of boiling sulphur was avoided. An error of .01 in δ causes an error of less than 1° in the calculated value of t at 1000° .

After a careful determination of the ice and steam points, the tube was heated as follows :—

TABLE I.

Number of Expt.	Date.	Maximum Temperature.	Number of Expt.	Date.	Maximum Temperature.
1.....	March 13.	77° C.	6.....	March 29.	810° C.
2.....	" 17.	319	7.....	" 30.	824
3.....	" 21.	650	8.....	April 3.	828
4.....	" 23.	640	9.....	" 7.	821
5.....	" 24.	740	10.....	" 8.	840

After the experiment of March 30, the ice and steam points were re-determined, and were found to have changed considerably. Accordingly, from this date, a re-determination of the fixed points was made after each exposure to a high temperature, and the values then obtained were used in the reduction of the observations of the preceding experiment. On account of the change, the observations of March 21-29 inclusive were not reduced.

In making an experiment the tube was heated to as high a temperature as possible, and observations of length and resistance were made. By diminishing the gas-supply the tube was then allowed to cool gradually, and when the temperature had become steady, length and resistance measurements were again made; this process was repeated till the tube reached the temperature of the air. The observations were recorded thus :—

TABLE II.

Time.	Glass tube.	Bench.	Porcelain tube.	R. L.	Coils.	Bridge wire.	Temp. of Coils.
7.37 P.M.		14.65	10.1285	70, 50	D, H	+1.5	15.63
7.54 „	10.4212	14.65					
8.17 „		14.9	10.2045	60, 40	B, C, E, F, G	+3.6	14.9

Columns 2 and 4 give the sum of the microscope readings for the standard length and the porcelain tube respectively. The porcelain tube projected from the furnace so that a length of about 6 cm. at either end was not directly heated thereby. The temperature of the tube in the neighbourhood of the marks was taken roughly by means of mercury thermometers, and is recorded in column 5.

The results of experiments 1, 2, 7-10, are collected in Table III. (p. 96); the results of the last four experiments are represented in the diagram.

It appears from the diagram that, from 0° to 600°, the results are represented fairly well by a curve given by the formula

$$l_t = l_0(1 + 34.25 \times 10^{-7}t + 10.7 \times 10^{-10}t^2).$$

Above 600° the points are more erratic, but at these higher temperatures the length measurements were somewhat difficult to make; moreover, as no gas-regulator was available,

it was impossible to keep the temperature quite steady during an observation. For comparison with the experimental numbers given in column 6, which represents the expansions reduced to unit length at 0°C ., column 7 gives

Ordinates: expansion per unit length: unit 10^{-5} .

Abscissæ: temperatures centigrade.

(The straight line above the lower curve represents the expansion according to Holborn and Wien's coefficient.)

the corresponding values calculated from the formula ; the full curves in the diagram are also drawn from the formula. The straight line in the diagram represents the expansion as given by Holborn and Wien's coefficient.

TABLE III.

No.	Date.	R.	<i>t</i> .	Lengths in cm.	Expan- sion per unit length.	From formula.	
1.	Mar. 13	277.5 341.0	14.1 77.4	91.3728 .3910	6×10^{-5} 26	5×10^{-5} 27	l_0 91.3673 (1) R_0 263.073
2.	Mar. 17	274.7 572.3	11.4 318.8	.3716 .4781	4 120	4 120	R_{100} 363.358 l_0 91.3683 (2)
7.	Mar. 30	1004.6 925.9 924.2 703.6 589.3 520.7 398.0 303.5	824.2 724.9 723.4 462.4 336.5 263.0 136.4 42.0	.7421 .6744 .6716 .5519 .5006 .4733 .4272 .3957	392.5 318.5 315.5 184.5 128.5 98.5 48 13.5	355 304.5 303.5 181 127.5 97.5 48.5 14.5	l_0 91.3833 R_0 260.467 R_{100} 361.788
8.	Apr. 3 Apr. 3	277.0 1005.4 898.2 801.4 675.1 561.7 454.3 360.7 299.0	16.1 827.5 692.5 576.3 431.5 307.3 194.2 98.8 37.3	.3860 .7165 .6381 .5912 .5318 .4834 .4413 .4084 .3877	3 372 286 235 170 117 71 35 12	5.5) 357 288.5 233 167.5 115 70.5 35 13	l_0 91.3765 R_0 260.875 R_{100} 361.903
9.	Apr. 7	996.4 971.3 897.1 762.8 495.3 291.2	821.5 789.2 695.6 534.3 237.7 29.0	.7036 .6811 .6336 .5646 .4552 .3874	358 333.5 281.5 206 86 12	354 336.5 290 213.5 87.5 10	l_0 91.3765 R_0 261.8 R_{100} 362.115
10.	Apr. 8	1011.4 957.4 920.2 801.9 681.8 593.4 502.6 406.6 315.6	839.5 770.0 723.1 579.3 440.9 342.5 245.0 145.1 53.1	.7316 .6913 .6633 .6002 .5404 .5030 .4678 .4321 .4023	379.5 335.5 304.5 235.5 170.5 129.5 91 52 19	363 327 303.5 234.5 172 130 90.5 52 18.5	l_0 91.3848 R_0 261.847 R_{100} 362.306

The coefficient of linear expansion at $t^{\circ}\text{C.}$ is given by

$$\frac{1}{l_0} \frac{dl}{dt} = 34.25 \times 10^{-7} + 21.4 \times 10^{-10}t.$$

Since the coefficient varies with the temperature, an uncertainty is introduced due to the gradient of temperature from the portion of the tube heated in the furnace to the marks; but this uncertainty must be very small. According to a rough estimate made by the aid of the auxiliary temperature readings in column 5, Table II., the correction for the ends came out to be .6 per cent. at mean temperature 800° , falling to .4 per cent. at 600° .

The error introduced into the temperature measurements, if the part of the tube occupied by the wire did not precisely coincide with the part between the diamond marks, must also have been very small. Thus, for a temperature gradient so steep as 100° per centim. in the neighbourhood of the diamond marks, an error of 1° in the temperature would necessitate a displacement of the wire by nearly 1 centim. The chief difficulty in experiments of this kind seems to be in insuring that the temperature shall be uniform all along the tube. With an ordinary gas-furnace it is impossible to be certain that this condition is satisfied. An accident to the tube after experiment 10 prevented any further measurements, and so no experiments were made while the temperature was *rising*.

As may be seen from Table III., there seem to have been permanent changes in the length of the tube during the course of the experiments, but these changes are very small and apparently irregular. At the end of experiment 7 it was observed that the tube had become very slightly bent; the irregularities in the length at 0° may be due to this. The total increase in length at 0° from March 13 to April 8 was .02 per cent.

For cubical expansions we get

$$v_t = v_0(1 + 102.75 \times 10^{-7}t + 32.4 \times 10^{-10}t^2);$$

and for the coefficient at t_0 ,

$$\frac{1}{v_0} \frac{dv}{dt} = 102.75 \times 10^{-7} + 64.8 \times 10^{-10}t.$$

In conclusion the writer must express his indebtedness for the use of the Sidney College Chemical Laboratory, and also for help which he has received from Mr. C. F. Green, B.A., from time to time.

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