The Effect of Stretching on the Thermal Conductivity of Wires

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XIV. *The Effect of Stretching on the Thermal Conductivity of Wires.* By A. JOHNSTONE, B.Sc.

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COMMUNICATED BY PROF. C. H. LEES, F.R.S.

OUTLINE OF METHOD USED.

1. Most observers, in determining the thermal conductivity of substances which conduct heat readily, have found it advisable to use the material in the form of wire and to let the heat flow along the axis. This method was adopted in the present experiments. The method is simplified if the heat flows from the centre of the wire to the two ends, which are kept at a constant temperature. In the following experiments the wire was surrounded by a vessel to ensure this, heat was supplied to the centre of the wire by passing a current of electricity through a manganin coil wound on the wire, and the temperature difference between two points on the same side of the centre was ascertained by means of two platinum coils also wound on the wire.

THE APPARATUS.

2. The wire to be tested AA , (Fig. 1) was fixed at each end between the jaws of screw clamps, B , joined to the brass cylinders, through which water could be circulated. To one clamp was attached a rod, T , passing through a framework, so that the tension could be applied by a nut working on a thread, T' ; and to the other was attached a spring balance, K , by which the tension was measured.

The heating coil H , was made from 14 cms. of No. 40 manganin wire closely wound on cylindrical sleeves of micanite, which could just slide on to the wire; 0.5 cm. of the wire was left unwound at each end, and to these ends were soldered covered copper leads of No. 30 gauge. The platinum thermometers (H , C , J') used were made from No. 40 single silk-covered platinum wire each of 35 cms. length, wound like the heating coil and having similar leads. This gave them a resistance of about 3 ohms at ordinary temperatures. The heating coil was placed at the centre of the wire under examination which was about 16 cms. long; one platinum thermometer was placed near to it, and the other near one of the clamps. For purposes of reference the former will be called the "hot coil" and the other the "cold coil." To support the leads from the

coils against breakage, each coil was tied by silk threads to a light wooden strip which it touched at two points and to which the leads were fixed. The coils were kept at a constant dis-

FIG. 1.—APPARATUS AND SCHEME OF CONNECTIONS.

tance apart by a cross strip of mica and were strengthened by a coating of shellac to prevent collapse during subsequent removal. The insulated leads from the coils were passed through

a brass tube in one of the end clamps to mercury cups in the wood frame, and the wire and end pieces were surrounded by a water jacket. Inside and touching the jacket was a supplementary platinum coil to enable changes in the jacket temperature to be detected.

The resistances of the coils were determined by means of a Callendar-Griffiths bridge, which was read in ohms to the fourth decimal place. For the galvanometer used a deflection of 1 mm. on the scale represented a difference of 0.0002 ohm, and for the coils used this would represent a temperature difference of about 0.01°C. For the conditions of the experiments performed this would enable a difference in the conductivity of 0.05 per cent. to be detected. The current to the heating coil was supplied by an accumulator and was regulated by an adjustable resistance. The current for the bridge was supplied by a Leclanché cell in series with an adjustable resistance. Each of the platinum coils could be connected in turn with the bridge at *P* through the mercury key as shown in the diagram.

THEORY OF THE METHOD USED.

3. If a thin rod of uniform cross section is entirely surrounded by air in a vessel kept at constant temperature, while heat is supplied to it near one end and the other is kept in good thermal contact with the wall of the vessel, then *

$$v = \frac{Q}{(phqk)^{\frac{1}{2}}} \cdot \sinh \left(\frac{ph}{qk} \right)^{\frac{1}{2}} x \Big/ \cosh \left(\frac{ph}{qk} \right)^{\frac{1}{2}} x_c \quad . \quad . \quad (1)$$

where *v* is excess of temperature of rod at the cross section *x* cm. from the end in contact with the vessel, over that of the vessel, *p* is the perimeter, *q* is the area of cross section, *h* the emissivity, *k* the thermal conductivity of the rod, and *Q* is the amount of heat per second crossing the section at any point *x_c*

If the heat is supplied at a uniform rate per centimetre to the surface of the rod between *x_c* and the free end, the mean temperature of the surface between *x_c* and the end may be taken as *v_c*, the temperature which would be observed at a point *x_c*, dividing the distance between *x_c* and the free end in the ratio 1:2, if the equation (1) held throughout the heated

* See Lees, Bakerian Lecture, "Phil. Trans." Roy. Soc. A 208, pp. 381, 443 (1908).

part of the rod. If s is the area of the surface of the rod beyond x_c and H is the total heat supplied to the rod, then

$$Q = H - h \cdot s v_c. \quad (2)$$

If the temperature excesses v_A and v_B of the rod over the air at two sections x_A and x_B are observed then,

$$k = \left\{ \frac{H(x_A S_A - x_B S_B)}{v_A - v_B} - h s x_c S_c \right\} / q \cosh \alpha x_c \quad (3)$$

where α is written for $(ph/qk)^{\frac{1}{2}}$ and S_A for $\sinh \alpha x_A / \alpha x_A$, &c.

From equation (3) k may be calculated with sufficient accuracy by taking, $\sinh \alpha x / \alpha x = \cosh \alpha x = 1$ approximately, and neglecting the term $\left(\frac{h s x_c}{q} \right)$, which, for the experiments described, introduces an error in k of approximately 0.003 per cent.

We thus get

$$k = \frac{H}{q} \cdot \frac{x_A - x_B}{v_A - v_B} \quad (4)$$

Since for any one experiment H , q , $x_A - x_B$, were constant we may take k proportional to

$$(v_A - v_B)^{-1}. \quad (5)$$

If R_1 is the resistance of the platinum thermometer used to determine v_A , and r_1 is that for v_B when both are at the jacket temperature, and if R_2 and r_2 are the corresponding values when a temperature difference exists; then it may be shown that

$$v_A - v_B = \frac{1}{B} \left(\frac{R_2 - r_2}{R_1 - r_1} \right) \quad (6)$$

where B is a constant.

Hence for any experiment we may take

$$k \text{ proportional to } \frac{1}{q} \left(\frac{R_2 - r_2}{R_1 - r_1} \right)^{-1} (x_A - x_B) (\text{current})^2. \quad (7)$$

In order to detect inconsistencies in readings during an experiment a method for finding $v_A - v_B$ approximately was also used.

METHOD OF EXPERIMENTING.

4. When taking a resistance reading for any of the coils, to avoid thermo-effects the galvanometer was kept in circuit and the deflection of the galvanometer noted when the Leclanché cell was connected to the bridge. At the beginning of an experiment tap water was circulated through the jacket and the resistance of the jacket coil was read at intervals. After about

45 minutes the temperatures usually became steady. The resistances of the "hot" and "cold" coils were then read. Then a suitable current was sent through the heating coil. After about 30 minutes the resistances of the coils had become steady and were again read. Owing to slight variations in the jacket temperature it was seldom possible to repeat these readings and obtain exactly the same values. Consequently an attempt was made to read the resistances of the two coils with as small a time difference as possible. A number of such double readings was taken and the mean temperature difference of the coil calculated. The resistance of the jacket coil was read at intervals to detect abnormal changes. The wire was then stretched by a force about 0.7 of the elastic limit and the resistances of the coils read again. The stretching force was then removed and readings again taken. The temperature difference between the hot and cold coils varied between 10°C. and 20°C.

The wires tested were all (except the nickel one, which was No. 16 gauge) of No. 14 gauge. When new wires were used the results for successive experiments were not consistent with each other until about the third experiment, owing probably to initial stresses in the wires; and the results were more consistent during the summer months, when the temperature of the jacket water was not affected by the heating apparatus. The effect of the stretching on the dimensions of the wire is neglected, as its influence on the conductivity is too small.

5. COMMENTS ON THE RESULTS.

For all the wires used, stretching produced a slight increase in thermal conductivity. Although difficulty was experienced in getting results which were consistent throughout, those obtained when conditions were most satisfactory show an increase of about 0.5 per cent. for a tension about 0.7 of the elastic limit. A few experiments apparently showed a decrease in conductivity of the order 0.1 per cent. with stretching, but in these cases the readings were always unsteady and unsatisfactory. In all cases when readings were steady an increase was observed. Several attempts were made to determine the change in conductivity for smaller tensions, and the results seem to indicate that the change is not appreciable until the tension approaches the elastic limit. After the tension was withdrawn the conductivity returned approximately to its original value, although in most cases the value was slightly in excess

OBSERVATIONS AND RESULTS.

Copper Wire, No. 14 Gauge. $x_A - x_B = 4.25$ cm.							
Date. 1914.	Duration of experi- ments. Hrs.	Tensions.		$\left\{ \frac{R_2 - r_2}{R_1 - r_1} \right\}^{-1}$ proportional to k .	Per- centage increase in k .	Current used to give H. Amps.	$\left\{ \frac{R_2 - r_2}{R_1 - r_1} \right\}^{-1}$ $\times (\text{current})^2$ $\times (x_A - x_B)$.
		Kilos.	Kilos/cm. ²				
July 8th...	4	0 15 0	463	26.88 26.98 26.90	0.37	0.3	10.28 10.32 10.29
Sept. 8th.	5	0 10 0	309	16.03 16.12 16.09	0.56	0.4	11.03 11.09 11.07
Sept. 9th.	6	0 10 0	309	15.82 15.84 15.82	0.13	0.4	10.88 10.90 10.88
Sept. 10th.	5	0 10 0	309	27.10 27.29 27.12	0.70	0.3	10.37 10.44 10.38
Sept. 11th.	5	0 10 0	309	27.03 27.25 27.10	0.81	0.3	10.34 10.42 10.37
Steel Wire, No. 14 Gauge. $x_A - x_B = 4.45$ cm.							
Oct. 21st.	4½	0 40 0	1,235	16.66 16.74 16.69	0.48	0.2	2.966 2.980 2.971
Oct. 28th.	4½	0 40 0	1,235	16.57 16.77 16.66	1.21	0.2	2.949 2.985 2.966
Nov. 4th.	4½	0 40 0	1,235	16.36 16.46 16.36	0.61	0.2	2.912 2.929 2.912
1915. Nickel Wire, No. 16 Gauge. $x_A - x_B = 4.75$ cm.							
June 23rd.	4	0 15 0	723	25.46 25.51 25.21	0.20	0.16	3.095 3.101 3.066
June 24th.	4	0 20 0	964	29.33 29.40 29.35	0.24	0.16	3.567 3.575 3.569
June 30th.	3½	0 20 0	964	25.51 25.66 25.50	0.59	0.16	3.104 3.120 3.100

Aluminium Wire, No. 14 Gauge. $x_A - x_B = 4.55$ cm.

Date. 1914.	Duration of experi- ments. Hrs.	Tensions.		$\left\{ \frac{R_2}{R_1} - \frac{r_2}{r_1} \right\}^{-1}$ proportional to k .	Per- centage increase in k .	Current used to give H . Amps.	$\left\{ \frac{R_2}{R_1} - \frac{r_2}{r_1} \right\}^{-1}$ $\times (\text{current})^2$ $\times (x_A - x_B)$
		Kilos.	Kilos/cm. ²				
Nov. 18th.	$4\frac{1}{2}$	0	463	14.64	0.27	0.3	5.995
		15		14.68			6.012
		0		14.68			6.012
Nov. 25th.	$4\frac{1}{2}$	0	463	18.66	0.48	0.26	5.740
		15		18.75			5.768
		0		18.66			5.740
Dec. 2nd...	3	0	463	18.94	1.27	0.26	5.826
		15		19.18			5.899
		0		18.79			5.780

Brass Wire, No. 14 Gauge. $x_A - x_B = 4.6$ cm.

Dec. 16th.	$4\frac{1}{2}$	0	463	15.51	0.26	0.2	2.854
		15		15.55			2.861
		0		15.44			2.841
Jan. 27th, 1915	4	0	463	15.20	0.33	0.2	2.797
		15		15.25			2.805
		0		15.19			2.795

1915.

Zinc Wire, No. 4 Gauge. $x_A - x_B = 4.65$ cm.

Mar. 3rd...	4	0	463	21.82	0.37	0.2	4.059
		15		21.90			4.072
		0		21.72			4.040
May 5th...	$4\frac{1}{2}$	0	463	21.17	0.28	0.2	3.938
		15		21.23			3.950
		0		21.21			3.945
May 12th.	4	0	463	21.93	0.46	0.2	4.079
		15		22.03			4.098
		0		unsatis- factory			unsatis- factory
May 19th.	$3\frac{1}{2}$	0	463	22.52	0.71	0.2	4.189
		15		22.68			4.218
		0		22.62			4.207
May 26th.	4	0	463	22.93	0.10	0.2	4.265
		15		22.96			4.271
		0		22.94			4.267

of the original value. The numbers quoted for k in the results are values proportional to the thermal conductivity.

The relative conductivities calculated from the values of the heating currents and of $x_A - x_B$, on the assumption that the conductivity of copper is 0.90 are: copper 0.90, steel 0.25, nickel 0.18, aluminium 0.50, brass 0.24, zinc 0.35, whose relation is of the right order.

The experiments described in this Paper were carried out at the suggestion of Prof. Lees, to whom I am indebted for the general design of the apparatus used and for valuable suggestions during the course of the work.

ABSTRACT.

In the experiments carried out, the wire to be tested was fixed at each end between the jaws of screw clamps joined to brass cylinders, through which water could be circulated. Attached to one clamp was a rod passing through a framework, enabling tension to be applied by a nut working on a thread.

Heat was supplied to the centre of the wire by passing a current of electricity through a manganin coil wound on the wire, and the temperature difference between two points on the same side of the centre was ascertained by two platinum coils, also wound on the wire.

The resistances of the coils were determined by means of a Callendar-Griffiths bridge, enabling a temperature difference of 0.01°C . to be read, and making it possible to detect a difference in conductivity of 0.05 per cent. If R_1 is the resistance of the platinum thermometer nearer the heating coil, and r_1 is that of the other platinum coil when both are at the jacket temperature; and if R_2 and r_2 are corresponding values when a temperature difference exists, then it may be shown that the conductivity

$$K \text{ is proportional to } \left(\frac{R_2 - r_2}{R_1 - r_1} \right)^{-1}.$$

For all the wires used (copper, steel, nickel, aluminium, brass, zinc), stretching produced a slight increase in thermal conductivity. The most satisfactory experiments showed an increase of about 0.5 per cent. for a tension of about 0.7 of the elastic limit.

After the tension was withdrawn the conductivity returned approximately to its original value.

DISCUSSION.

Mr. F. E. SMITH suggested that it would have been of interest if the author had made simultaneous observations of electrical conductivity on the same apparatus. Had any experiments been made on liquids, such as mercury, for example?

Prof. BOYS asked if the coefficient would be reversed if compression were applied instead of extension. He realised there would be some practical difficulties in making the experiments.

Prof. LEES, in reply, said that there would have been electrical measurements included in the Paper but for the author's absence in the Army. He thought compression measurements could be made, though they had not so far been carried out.