THERMOELECTRIC ELECTRIC EFFECTS IN IRON AND MERCURY DUE TO ASYMMETRIC HEATING.

By J. M. Benade.

Synopsis.

Thermo-electric Effect Due to Temperature Gradient Along a Constriction.—(1) *Iron rod.* Using constrictions from 0.5 to 4 mm. in diameter and from 0.5 to 1.5 mm. in length, electromotive forces were obtained with gradients of a few degrees per mm. large enough to be measured easily with a sensitive galvanometer. For each constriction the effect was found to be proportional to the temperature gradient. The fact that it decreased as the mean temperature was increased indicates that it is not an inverse Thomson effect. Moreover it depends on the dimensions of the constriction, being less for the smaller diameters. (2) *Mercury.* By using two relatively large quantities of mercury connected through a pin hole in an intervening sheet of mica, a temperature gradient of at least 600° C. per m.m. could be maintained in the constriction, but a high sensitivity galvanometer failed to indicate any electromotive force although according to Benedick's conclusions[1] a deflection of over 50 divisions should have been observed. His results are explained as due to a true thermo-electric effect between the mercury and the slate tube containing it. (3) *In explanation* it is suggested that the effect is associated with the non-homogeneity produced by the mechanical stresses set up in the iron as a result of unequal thermal expansion and is not due merely to the flow of heat through the constriction.

It has been generally assumed that the e.m.f. produced by the asymmetric heating of conductors is an inverse Thomson thermoelectric effect. It was on this assumption that an attempt was made to measure the temperature coefficient of the Thomson effect by observing the rate of change of this thermo-e.m.f. with a change of mean temperature of a constriction in various metals, the temperature gradient in the constriction being maintained constant. With this object in view various forms of apparatus were used, the one shown in Fig. 1 being typical. The temperature gradient in the constriction as well as the absolute temperature was controlled by means of heating coils. The temperatures were measured by means of the usual copper constantan thermo couples, which it was found necessary to insulate carefully from the rod into which they were inserted. To the ends of the rod were soldered iron wires and to these in turn copper wires which were connected to a high sensitivity galvanometer. In order to prevent spurious thermoelectric effects both pairs of junctions were kept in constant temperature baths.

The thermo-junctions protected by thin-walled glass capillary tubes were inserted into holes 1.5 mm. in diameter in the iron rod on opposite

[1] Comptes Rendus, 169, No. 13, Sept. 29, 1919.

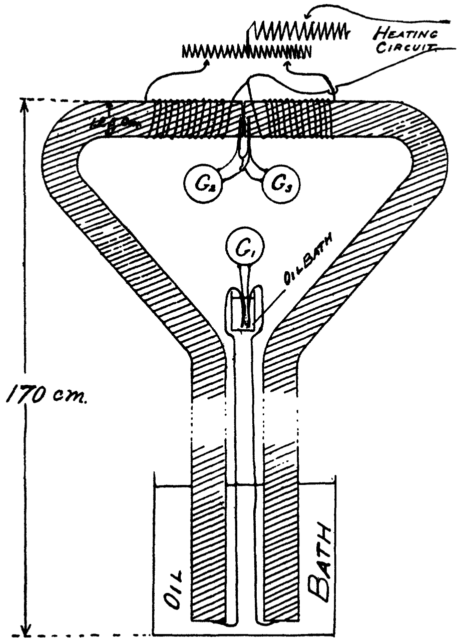
HEATING
CIRCUIT
G_2
G_3
G_1
OIL BATH
170 cm.
OIL
BATH

Fig. 1.

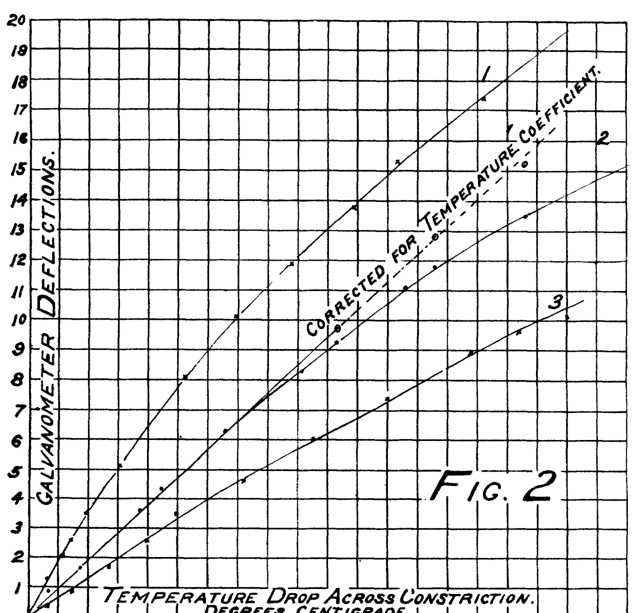
GALVANOMETER DEFLECTIONS.
TEMPERATURE DROP ACROSS CONSTRICTION.
DEGREES CENTIGRADE.
CORRECTED FOR TEMPERATURE COEFFICIENT.
1
2
3
FIG. 2
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
18
20
5°
10°
15°
20°
25°
30°
35°
40°
45°
50°

Fig. 2.

sides of the constriction with a distance of about 4 mm. between their centers. The constrictions varied from 4 mm. to 0.5 mm. in diameter and from 1.5 mm. to 0.5 mm. in length. It was found that for very sharp constrictions with correspondingly abrupt temperature gradients, for a given difference of temperature between the ends of the constrictions relatively small e.m.f.'s were obtained. The greatest effects were obtained when the constrictions were not very deep, though this point has not been carefully investigated. The important fact for our present purpose is that the e.m.f. is found to depend not merely upon asymmetry in the temperature gradient but also upon the dimensions of the constriction. This is shown by the curves in Fig. 2, and in Fig. 3.

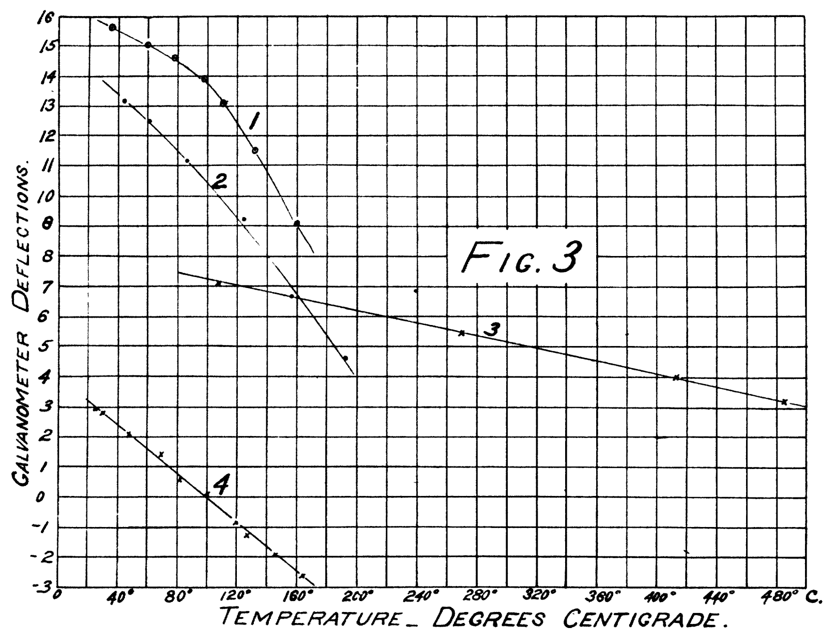

Fig. 3.

The curves in Fig. 2 show the relation between the e.m.f. and the temperature gradient in the constriction. Were it not for the fact that the mean temperature of the constriction during each run was constantly rising, the curves would have been rectilinear, for, as will be later shown the temperature coefficient of the effect is negative. In other words the e.m.f. for a particular apparatus is directly proportional to the temperature gradient in the constriction. It is assumed always that the only asymmetry in the temperature gradient is at the constriction. Small errors are actually introduced because this is not always strictly true, though in general these errors are negligible. Curves 1, 2 and 3 were obtained under similar conditions except that the constriction was reduced after getting the data for the first, and again after the readings for the second curve, the third curve corresponding to the sharpest constriction. These curves show clearly that for given differences in temperature between the ends of the constriction the e.m.f. actually decreases as the abruptness of the temperature gradient increases.

In order to measure the temperature coefficient of the effect for any particular form of apparatus, the e.m.f.'s corresponding to mean temperatures of the constriction in which the temperature gradient was maintained constant, were observed. For this purpose a temperature difference between the ends of the constriction of about 20° C. was sufficient to produce convenient galvanometer deflections. In Fig. 3 are several typical curves representing the variation of the e.m.f. with the mean temperature of the constriction. The curves show that in each case the temperature coefficient is negative,[1] *i.e.*, the e.m.f. produced by a constant temperature gradient in the constriction decreases as the temperature rises. The value of this coefficient is found to depend upon the size and form of the constriction as well as upon the material concerned. The variations in the degree of slope and especially the direction of slope show definitely that the effect is not simply an inverse Thomson effect, for in that case the slope should be the same in all cases and should show a positive temperature coefficient as found by Berg,[2] and others. It seems probable that the effect is due to mechanical stresses set up in the iron by unequal thermal expansion which in some way alter the structure of the metal in or near the constriction sufficiently to give rise to the observed thermoelectric effects, as has been repeatedly suggested.

The unexpected results above recorded indicated that the observed e.m.f.'s are due to a lack of homogeneity in the asymmetrically heated conductor. The crucial test for the existence of the effect is its detection in the case of mercury. Benedicks[3] claims to have observed and measured the effect in mercury though Haga and Zernike[4] using a very much better form of apparatus conclude that there is no true effect due merely to asymmetric heating of the conductor. Repeated attempts with various forms of apparatus were made but with negative results in each case though an effect of the same order of magnitude as that obtained in iron should have been very easily obtained. A diagram of the final form

[1] Curve No. 4 which indicates a reversal of the effect is rather less reliable than the others though there is no reason to believe that it is not correct. The apparatus was broken before getting other readings.

[2] Annalen der Physik, Vol. 32, 1910, p. 477; Vol. 33, p. 1195.

[3] Comptes Rendus, 169, No. 13, Sept. 29, 1919.

[4] K. Akad. Amsterdam, Proc., XXI 10, p. 1262, 1919.

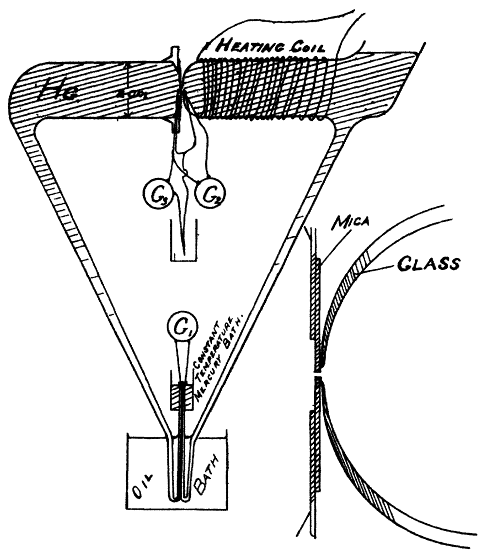

Fig. 4.

of apparatus used is shown in Fig. 4. The relatively large quantity of mercury used was contained in two tubes connected together by means of a pin-hole 0.35 mm. in diameter through an intervening sheet of mica 0.3 mm. in thickness. For the galvanometer connections smaller glass tubes were sealed on to the larger ones and suitably drawn out so that the necessary junctions with the galvanometer lead wires could be kept at exactly equal temperatures by means of a cup of mercury, in order to avoid all spurious thermoelectric effects. Differences in temperature on opposite sides of the constriction were measured by means of thermocouples encased in very fine capillary tubes. The galvanometer used gave deflections of one scale division per 10^{-8} volt, which though not so sensitive as the one used by Benedicks was sufficiently sensitive for the purpose. With this arrangement it was quite possible to keep the mercury on one side of the constriction at or below room temperature indefinitely while the mercury on the other side was slowly boiling. Though it was of course not possible to determine accurately the temperature gradient in the constriction it must have been not less than 600° C. per mm. and was probably nearly if not quite 1000° C. per mm. when the temperature difference between the two sides of the mica was 330° C. or more. Special care was taken in constructing the apparatus to reduce to the minimum conduction of heat from one side to the other through the glass and mica and at the same time to make full use of convection currents in the mercury. The only deflections obtained amounted to four or five scale divisions and these were found to be due entirely to leakage from the heating circuit. Had there been an effect of the magnitude affirmed by Benedicks a deflection of at least 50 scale divisions should have been obtained, for the temperature gradient in the present experiment must have been very much greater than it is possible to obtain in small glass or slate tubes.

If there were in mercury an effect of the same type as that obtained by the asymmetric heating of solid conductors the order of magnitude of the effect would probably be the same as in iron, in which case a drop of 0.005° C. in the constriction should have produced an appreciable deflection, though an actual drop of more than 330° C. produced no observable effect. Since it has been suggested that an e.m.f. may be produced by the rapid conduction of heat across a constriction a modification of the above described apparatus was made in order to test this hypothesis. As described the apparatus was designed to reduce heat conduction to a minimum so that if this were the true explanation of the effect at most only a small effect would have been obtained. The pin-hole in the mica separating the two sections was enlarged to a diameter of about 2 mm. With this arrangement heat was rapidly conducted through the constriction though as before there was absolutely no indication of the existence of any e.m.f. in the circuit.

In explanation of the results obtained by Benedicks and of his cubic relationship, *i.e.*, that the e.m.f. produced in mercury when heated on one side of a constriction in a tube is proportional to the cube of the temperature drop in the constriction, it is suggested that the effect measured was due entirely to a true thermo-e.m.f. produced by the mercury and slate, the abnormal rate of increase being caused by the change in the conductivity of the slate containing-tubes. The thermo-e.m.f. produced by the slate mercury couple with 300° C. difference in temperature between the junctions is very large indeed in comparison with the quantities measured and the conductivity of slate is not extremely low, so that even though the mercury column was continuous the relatively small e.m.f.'s observed may thus be fully accounted for If this be the correct explanation it is to be expected that the effects in glass will be smaller. The apparatus described above should be nearly if not entirely free from the possibility of disturbances of this nature.

Results.—It seems to be definitely shown that if there be any true thermoelectric effect in mercury due to asymmetric heating it must amount to less than 10^{-8} volt for a gradient of 600° C. per mm. Also that if there be any effect due to a flow of heat it must be extremely small.

The effect in the case of iron and presumably of other metals is not an inverse Thomson effect. Since there is no effect in mercury to compare with that observed in solids it may be assumed that non-uniform temperature gradients in solids sufficiently disturb the homogeneity of the material to give rise to the observed e.m.f.'s and that these effects are not due simply to a flow of heat across a constriction.

Physical Laboratory,
Forman Christian College,
Lahore, India.