# THE LEDUC EFFECT IN SOME METALS AND ALLOYS.

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If a metal plate having a longitudinal flow of heat in it is placed in a magnetic field which is perpendicular to the plane of the plate, a transverse difference of temperature is observed. This effect may be described as a rotation of the isothermal by the magnetic field and is known as the Leduc effect. This transverse difference of temperature $\Delta\theta$ will be determined by the width of the plate $w$, the longitudinal temperature gradient $\partial T/\partial x$, the magnetic field $H$ and the nature of the plate. The coefficent of the Leduc effect ${}_hT_h$ is given by the equation,

$$\Delta\theta = {}_hT_h\, wH \cdot \frac{\partial T}{\partial x}.$$

According to the notation of Hall and Campbell[1] which is being followed, the $T$ calls attention to the fact that the observed effect is at right angles to the longitudinal flow of heat; the subscript $h$ preceding $T$ indicates that the longitudinal flow is thermal and the other subscript $h$ indicates that the transverse effect is thermal. Fig. 1 shows the accepted convention as to the sign of the coefficient. The rectangle represents the metal plate to be investigated; the arrows at either end of the plate, the direction of the longitudinal heat current and the arrows on the circle, the direction of the magnetizing current. If the rotation of the isothermal is in the direction in which the magnetizing current flows, the coefficient ${}_hT_h$ is said to be positive.

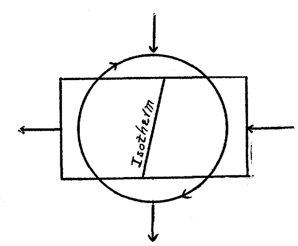


Fig. 1.

The plates used for this investigation were about 3 cm. long, 1.7 cm. wide and 1 or 2 mm. thick. In Fig. 2 is shown a plate with the copper-advance thermal couples attached for measuring the longitudinal temperature gradient and the transverse change of temperature. The longitudinal thermal couples $C$ and $D$ were soldered to the surface of the plate; the transverse ones $A$ and $B$ were imbedded in the edges of the plate and held in position by as small amount of solder as possible. The thermal junctions which were not soldered to the plate were in each case

[1] Proc. Am. Acad. of Arts and Sci., 46, p. 625 (1911).

immersed in a constant temperature-bath which was kept at room temperature. The thermoelectric heights of these thermal couples were determined over the range of temperature used in these experiments. The plate was soldered to copper projections from two rigidly connected copper tubes. Through one of these tubes flowed water at room temperature; through the other, steam. The plate was enclosed in a thin box of hard rubber or black fibre and the box was filled with magnesia oxide. The plate was then rigidly mounted between the poles of the electromagnet.

The couples with which the longitudinal temperature gradient was determined were used in the usual manner with a slide-wire potentiometer. The transverse temperature difference set up by the magnetic action was determined by connecting the thermal couples which were connected to the opposite sides of the plate, differentially to the coils of a Broca galvanometer. Since these couples could not be located exactly on the same isothermal, the galvanometer would in general show a deflection before the magnetic field was established. In order to compensate for any such inequality of thermoelectromotive forces tending to give a deflection of the galvanometer a slide-wire potentiometer was arranged in series with one of the coils of the galvanometer so that any electromotive force necessary to bring the galvanometer needle to its zero position could be introduced. The magnet was placed about 30 feet from the galvanometer and so oriented that the excitation of magnet produced less than a millimeter deflection in the galvanometer on open circuit. With the plate in position between the poles of the magnet a steady stream of water at room temperature was passed through one of the copper tubes and steam, through the other. When the flow of heat had become steady, the galvanometer circuit was closed and the slider on the potentiometer was adjusted so that the galvanometer showed no deflection. With the galvanometer circuit open the magnetic field was established. As soon as conditions of equilibrium had been reached, the deflection of the galvanometer corresponding to the change of temperature at the edges of the plate was noted. The observations were repeated with the magnetic field reversed. The mean of these observations was taken as the deflection corresponding to the change of

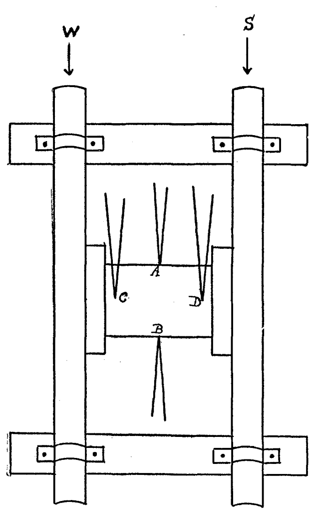

Fig. 2.

temperature due to the magnetic action. Three or more such sets of observations were taken for each magnetic field. From the average of these deflections, the sensibility of the galvanometer and the thermoelectric height of the thermal couple the transverse change of temperature between the edges of the plate was calculated. The mean of the temperatures of the ends of the plate was taken as the temperature of the middle of the plate and, therefore, the temperature at which the Leduc coefficient was determined. The deflection increased for nearly a minute after the excitation of the magnet. The readings were taken when a constant deflection had been reached. The sensibility of the galvanometer which for a fixed scale distance of about 200 cm. amounted to about $5 \times 10^{-7}$ volts per cm. was taken for each series of observations.

In Table I. are given the results for nickel, nichrome, electrolytic

Table I.

| Nichrome, $T = 56.9°$. | | Nickel, $T = 61°$. | |
|---|---|---|---|
| $H$ | $\frac{\Delta\theta}{w} \div \frac{\partial T}{\partial x}$. | $H$ | $\frac{\Delta\theta}{w} \div \frac{\partial T}{\partial x}$. |
| 2,130 | $16.7 \times 10^{-4}$ | 2,340 | $34.9 \times 10^{-4}$ |
| 4,320 | 33.6 | 4,300 | 58.6 |
| 6,550 | 39.0 | 6,320 | 66.4 |
| 7,970 | 41.9 | 8,500 | 67.3 |
| 9,120 | 41.9 | 10,880 | 68.9 |
| 9,820 | 41.9 | | |
| 10,800 | 41.9 | | |

| Electrolytic Iron, $T = 56.9°$. | | Cobalt, $T = 53.7°$. | |
|---|---|---|---|
| $H$ | $\frac{\Delta\theta}{w} \div \frac{\partial T}{\partial x}$. | $H$ | $\frac{\Delta\theta}{w} \div \frac{\partial T}{\partial x}$. |
| 4,284 | $18.1 \times 10^{-4}$ | 4,200 | $29.2 \times 10^{-4}$ |
| 6,650 | 27.5 | 6,600 | 44.3 |
| 8,200 | 34.4 | 8,000 | 52.4 |
| 11,900 | 46.7 | 11,800 | 75.6 |
| 15,800 | 62.9 | 15,800 | 86.4 |
| 18,900 | 74.6 | 18,900 | 86.5 |
| 21,400 | 79.0 | 21,400 | 86.4 |
| 23,100 | 81.2 | | |

iron and cobalt. The nickel and cobalt were obtained from Kahlbaum. The electrolytic iron was kindly furnished by Professor Burgess, of the University of Wisconsin. It has been shown that this iron is very free from impurities. In Table I. $T$ is the temperature at the middle of the plate where the effect was observed; $H$ is the magnetic field in gausses; $(\Delta\theta/w) \div (\partial T/\partial x)$ gives the transverse change of temperature in degrees Centigrade for a plate one centimeter wide with a longitudinal temperature gradient of one degree Centigrade per centimeter in it. These results are also shown graphically in Fig. 3, where field strengths in gausses have been plotted as abscissæ and $(\Delta\theta/w) \div (\partial T/\partial x)$ as ordinates. It will be observed that the Leduc effect in nickel is opposite to that in

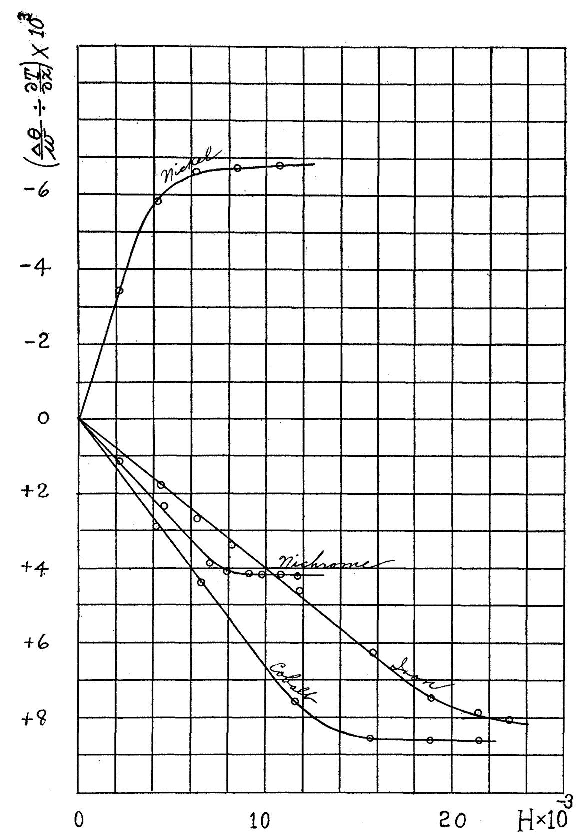


Fig. 3.

iron, cobalt and nichrome. For lower magnetic fields the effect is nearly proportional to the intensity of the magnetic field. For sufficiently high magnetic fields the difference of temperature set up by the magnetic action approaches a constant value. The curves showing the dependence of the Leduc effect on the magnetic field are exactly like those showing the dependence of the Hall effect and the Nernst effect on the magnetic field. In each of these three cases the effect is proportional to the intensity of magnetization in the plate and not to the magnetic field. The observed effect, therefore, reaches a maximum value when the intensity of magnetization has reached its greatest value.

In Table II. are recorded the Leduc coefficients ${}_hT_h$ for a number of metals studied together with the field strength and the temperature at which the observations were made. The sign prefixed to the coefficient indicates the direction of the effect according to the convention explained earlier in this paper. The values for iron, zinc and antimony are in good agreement with the corresponding values given by Zahn[1] but the values for nickel and cobalt do not agree well with his values. For the sake of

Table II.

| Metal. | $H$ | ${}_hT_h \times 10^8$ | Temp. °C. |
|---|---|---|---|
| Nickel.................. | 10,880 | − 61.5(20) | 61.0° |
| Cobalt.................. | 11,800 | + 64.0(13) | 53.7° |
| Nichrome............... | 10,800 | + 38.8 | 59.3° |
| Electrolytic iron......... | 11,900 | + 39.2(39) | 56.9° |
| Molybdenum............ | 12,300 | − 17.5 | 57.5° |
| Tungsten............... | 12,200 | + 15 | 58.6° |
| Cadmium............... | 12,200 | + 11 | 60.5° |
| Zinc.................... | 10,900 | + 12.4(12.9) | 58.5° |
| Antimony.............. | 11.000 | +262.0(200) | 56.7° |

comparison Zahn's values have been inserted in brackets. For a field of 6,290 gauss Zahn gives for another specimen of nickel the value, $-55 \times 10^8$. For iron Hall and Campbell found ${}_hT_h = +632 \times 10^9$ at 60° C. The lack of agreement between these observed values of ${}_hT_h$ must be attributed for the most part to the impurities in the metals and to their previous treatment.

The Leduc effect in two series of alloys—bismuth-antimony and antimony-zinc—has been studied. In the bismuth-antimony series of alloys the dependence of the effect on the intensity of the magnetic field was investigated for each of the plates. The results of these observations have been represented in Fig. 4. In this figure the transverse difference of temperature for a plate one centimeter wide with a temperature gradient of one degree Centigrade per centimeter has been plotted as ordinates and the magnetic field in gausses as abscissæ. It is seen from this figure that the transverse difference of temperature in bismuth and the alloys which contain a large percentage of bismuth increases less rapidly than the magnetic field. On the other hand in antimony and the alloys which contain a large percentage of antimony there is a linear

[1] Ann. der Phys., 14, p. 886 (1904).

relation between the magnetic field and the transverse difference of temperature. The sign of the effect in antimony is opposite to that in bismuth. To show the dependence of the Leduc coefficient on the composi-

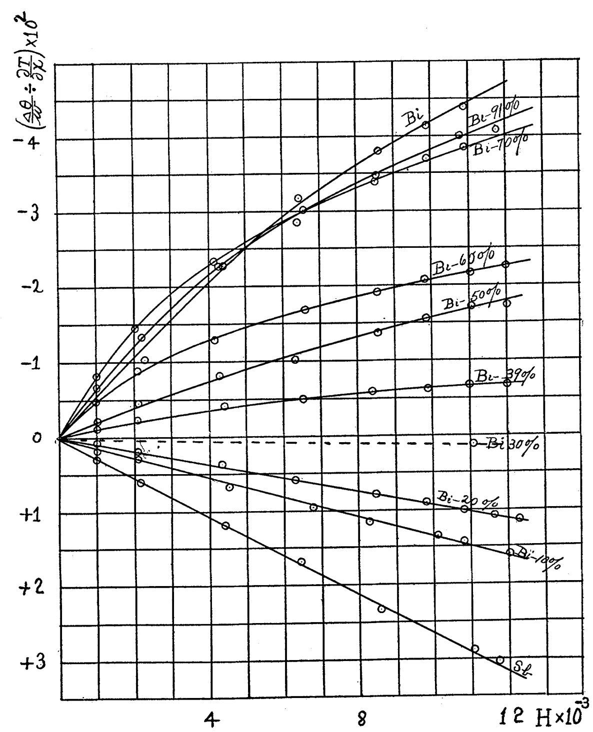


Fig. 4.

tion of the alloy Fig. 5 has been plotted with the Leduc coefficients as ordinates and the percentages by weight of antimony as abscissæ. The Leduc coefficients plotted in Fig. 5 were determined at a temperature of about 52° C. and with a magnetic field of about 11,000 C.G.S. units. The addition of antimony to the bismuth decreases the Leduc coefficient. When the alloy contains somewhat less than 70 per cent. of antimony the direction of the effect is reversed and for alloys containing more than this amount of antimony the direction of the effect is positive. The data from which this curve was plotted have been given in Table III.

In the antimony-zinc series the Leduc coefficient for each alloy was determined only for one intensity of the magnetic field which was in the neighborhood of 11,000 C.G.S. units. The temperature on the isothermal midway between the ends of the plate was about 57° C. This is, therefore, the temperature at which the coefficients were determined. Table

TABLE III.

| Composition. | | ${}_hT_h \times 10^8$ | $H$ |
|---|---|---|---|
| Per Cent. Sb. | Per Cent. Bi. | | |
| 0 | 100 | −405 | 10,900 |
| 9 | 91 | −375 | 10,800 |
| 30 | 70 | −354 | 11,000 |
| 40 | 60 | −195 | 11,000 |
| 50 | 50 | −154 | 11,000 |
| 61 | 39 | − 60 | 12,000 |
| 70 | 30 | + 9.5 | 11,100 |
| 80 | 20 | + 95 | 10,800 |
| 90 | 10 | +132 | 12,060 |
| 100 | 0 | +262 | 11,000 |

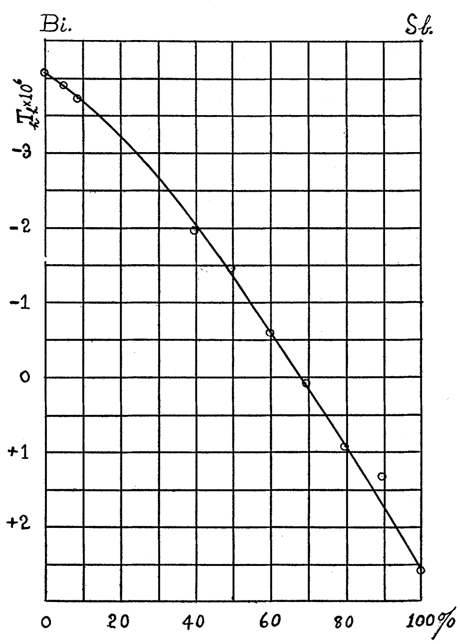

Fig. 5.

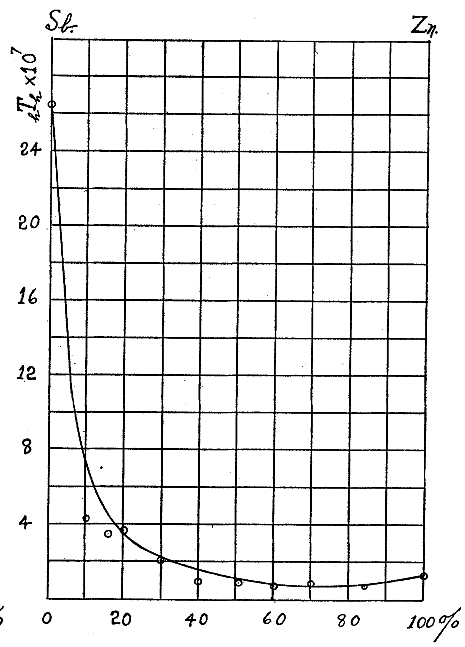

Fig. 6.

IV. gives the data on this series of alloys. These data have also been plotted in Fig. 6. The ordinates are the Leduc coefficients and the abscissæ the percentages by weight of zinc. The addition of a small percentage of zinc causes a very rapid decrease in the Leduc effect, so that when the alloy contains about 20 per cent. of zinc the Leduc coefficient is slightly more than one tenth as large as that in pure antimony. With the further addition of zinc the coefficient seems to pass through a not very well defined minimum.

TABLE IV.

| Composition. | | $_hT_h$ | $H$ | Temp. °C. |
|---|---|---|---|---|
| Per Cent. Sb. | Per Cent. Zn. | | | |
| 100 | 0 | +262 | 11,000 | 56.7° |
| 90 | 10 | 42.7 | 10,900 | 56.5° |
| 84 | 16 | 32.0 | 10,900 | 57.2° |
| 80 | 20 | 27.5 | 10,900 | 57.1° |
| 70 | 30 | 20.9 | 10,900 | 57.5° |
| 60 | 40 | 9.08 | 10,900 | 57.2° |
| 50 | 50 | 8.50 | 10,900 | 55.7° |
| 40 | 60 | 6.77 | 10,900 | 57.2° |
| 30 | 70 | 8.40 | 10,900 | 55.3° |
| 16 | 84 | 6.60 | 10,900 | 61.8° |
| 0 | 100 | 12.4 | 10,900 | 58.5° |

## SUMMARY.

1. In the magnetic metals nickel, nichrome, iron and cobalt, the transverse difference of temperature set up by the magnetic action in the case of the Leduc effect is proportional to the intensity of magnetization in the plate and not to the intensity of the magnetic field. This difference of temperature, therefore, reaches its maximum value when the intensity of magnetization has become a maximum. The relation of this effect to the magnetic field which produces it is the same as the relation of the Hall effect and the Nernst effect to the magnetic field. In antimony the Leduc coefficient is independent of the intensity of the magnetic field.

2. The Leduc coefficient has been determined in tungsten, molybdenum, cadmium, a series of alloys of antimony and bismuth and a series of alloys of antimony and zinc.

3. The addition of antimony to bismuth decrease the Leduc coefficient but less rapidly than is to be expected from the additive law. The addition of zinc to antimony causes a very rapid decrease in the Leduc coefficient. An alloy containing 10 per cent. of zinc and 90 per cent. of antimony has Leduc effect only about one sixth of that in pure antimony. With the further increase in the amount of zinc the coefficient decreases to a not very well defined minimum from which it rises to the value in zinc.

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