Transformation of electric in caloric energy (Joule's law)

Literature: Bergmann-Schaefer, II, 1958, para. 28
Pohl, Mechanik, 1955, para. 136

Principle: A calorimetric method is used to determine the quantity of heat Q generated by a steady electric current. It is found that $Q = \text{const.}\ VIt$.

One of the characteristics of electric current is the heat generated by it in current-carrying conductors. Simple examples of this are known from daily experience: the incandescent lamp, the immersion heater, the electric iron, and others. In 1841, Joule investigated the dependence of the quantity of heat Q generated by a steady electric current on the current I, the resistance R of the conductor in which the heat is generated, and the time of observation t. His result was $Q = I^2 Rt$. This relation, known as Joule's law, can be verified experimentally in the following way.

The apparatus used for this purpose is a water calorimeter with good heat insulation into which two resistance coils acting as immersion heaters are inserted. These are so attached to an insulating lid (see Fig. 1 on the reverse), that they can be used singly, in series, or in parallel. Thus the resistances 1 R_S (resistance of one coil $\approx$ 1 ohm), 2 R_S, or $\frac{1}{2}$ R_S can be used for the experiment.

Table 1 shows a worked example. A rheostat was used to obtain equal currents (I = 2.5 A) and these were maintained for equal lengths of time (t = 286 s). The increases of temperature obtained in this manner while the water was continuously stirred are shown in °C as ΔT.

Table 1

Circuit	Resistance	I in A	t in s	ΔT in °C
2 coils in series	2 R_S	2.5	286	4.0
1 coil	1 R_S	2.5	286	2.0
2 coils in parallel	$\frac{1}{2}$ R_S	2.5	286	1.0

The duration t of the experiment was so chosen that a rise in temperature of $\Delta T = 4$°C was obtained if $R = 2R_S$. Then the rise in temperature for R = 1 R_S was just half as great and that for $R = \frac{1}{2}$ R_S was just a quarter of that obtained if R = 2 R_S. Thus the rise in temperature and, therefore, the quantity of heat Q generated in equal periods t by equal currents I is proportional to the resistance R of the conductor under consideration: $Q \sim R$.

In a second series of experiments the relation between the rise in temperature and the current I is investigated. Table 2 shows a worked example:

Table 2

Circuit	Resistance	I in A	t in s	ΔT in °C
2 coils in series	2 R_S	3	428	9.0
2 coils in series	2 R_S	2	428	4.0
2 coils in series	2 R_S	1	428	1.0

Again, the time for which observation was continued was determined by a preliminary experiment so that the rise in temperature was just ΔT = 9.0° C for I = 3 A. ΔT was reduced to $^4/_9$ if I was reduced to $^2/_3$ of its original value, and to $^1/_9$ if I was reduced to $^1/_3$. The rise in temperature and, therefore, the quantity of heat Q generated in the resistor R during the time t is proportional to the square of the current I, $Q \sim I^2$.

In a third series of measurements we finally investigate the relation between the increase of temperature and the duration of the experiment. The results are shown in Fig. 2 (on the reverse). It will be seen that for equal currents and resistances, the increase of temperature ΔT and, therefore, the generated quantity of heat Q is proportional to the duration t of the experiment: $Q \sim t$.

By combination of the results of all three series of measurements we obtain the relation $Q = \text{const.}\ I^2 Rt$. Since $R = V/I$ this experimental result can also be written in the form $Q = \text{const.}\ I^2 Rt = \text{const.}\ VIt = \text{const.}\ V^2t/R$. The constant factor occurring in this derivation of Joule's law depends on the units in which the quantity of heat, the electric quantities, and the time are measured. If the resistance is in ohms, the current in amperes, the time in seconds, and the heat in calories, the constant has the value 0.2390 cal/J. Details on the subject will be found in Physics Leaflet DC 537.321; b.

The values shown in Tables 1 and 2 can be supplemented by measuring the voltages applied to the two heating coils. In this manner the resistances of the coils can also be found. In the worked examples given here they were 0.94 ohms for each separate coil, or 1.88 ohms if they were connected in series, and 0.47 ohms if they were connected in parallel.

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Apparatus required for the experiment:
(in order of assembly)

	Cat. No.
1 Joule's calorimeter	384 20
1 Dewar vessel with base	386 48
1 Thermometer	382 35 or 382 36
1 Rheostat, 11 Ω, 8 A	537 26
1 Demonstration multirange meter	531 86
As source of current e. g.	
1 Demonstration transformer, consisting of	
1 U-core with yoke	562 11
1 Clamping device	562 12
1 Coil with 500 turns	562 14
1 Coil with 46 turns	562 18
or	
1 or 2 Nickel-cadmium accumulators	522 70/71/73
1 Cut-out switch	504 45
1 Stopclock with clockwork	313 05
Connecting leads	501 92–95

Assembly:

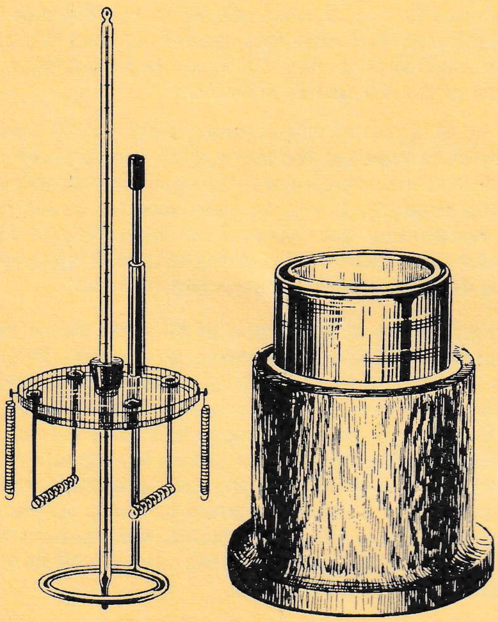

Fig. 1 Joule's calorimeter with two resistance coils, stirrer and hole for inserting the thermometer

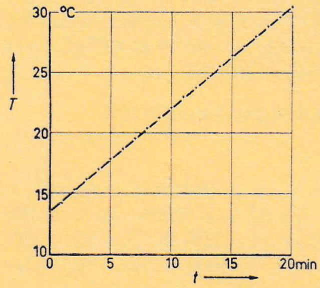

Fig.2
Temperature T as a function of the duration t of the experiment at constant current $I = 2.5$ A throuh a coil of resistance $R = 2\,R_S$

Useful hints:

1. The use of Joule's calorimeter is described in Directions for Use 384 20.
2. The heating coils and the mercury bulb of the thermometer must be completely immersed in water.
3. The heat insulation of the apparatus is relatively good, but excessive differences between the calorimeter temperature and the ambient temperature should be avoided. The linear increase of the temperature might otherwise be distorted by heat exchange with the surroundings, especially if the experiment is carried on over some length of time. The best course is to select the initial and final temperatures so that the ambient temperature is midway between them.
4. The greatest accuracy is obtained in case of measurements with D. C. from a well-charged accumulator. In case of the above-mentioned A. C. source (demonstration transformer) as well the limits of error are small and are mainly determined by the instruments used, in particular the temperature reading.
5. Rectified A. C. (for example, demonstration transformer with rectifier in series) may not be used, seeing that the wave form error causes a considerable deviation of the indication of the moving coil instrument. It would rather be possible to determine the wave form error of a rectifier from the experiment, and the theorem of the conservation of energy.