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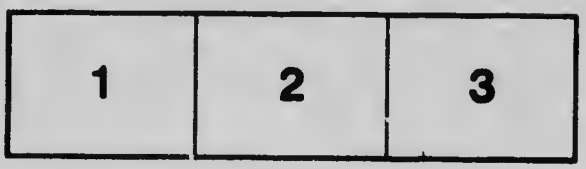
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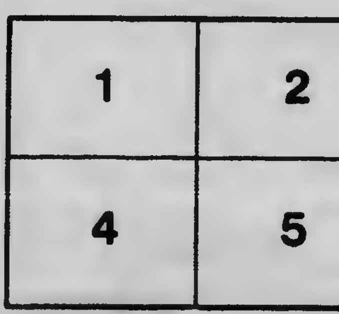
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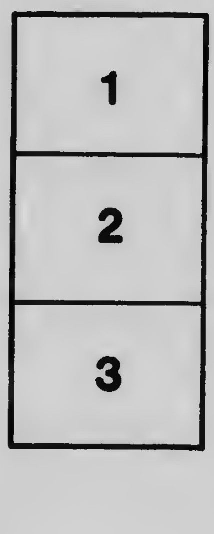

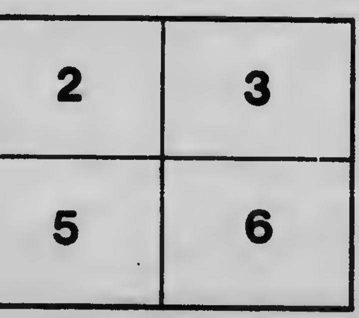

UNIVERSITY OF TORONTO STUDIES

PAPERS FROM THE CHEMICAL LABORATORIES

No. 47: A MECHANICAL MODEL TO ILLUSTRATE THE GAS LAWS, BY FRANK B. KENRICK

(REPRINTED FROM THE JOURNAL OF PHYSICAL CHEMISTRY, VOL. VIII)

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A MECHANICAL MODEL TO ILLUSTRATE THE GAS LAWS

BY FRANK B. KENRICK

The difficulty of getting elementary students to grasp the fundamental ideas of the gas laws, Carnot's cycle, the entropy function, etc., must have confronted every teacher of physical chemistry. The student learns all too easily that " peevee equals enartee ", but the apparent simplicity of the relations and the absence of concrete conceptions and numerical examples — to say nothing of absence of interest — combine to create a state of vagueness which will often hamper his progress for years. In order to overcome this difficulty the writer has constructed a simple model which has worked admirably, not only in giving students definite conceptions of Carnot's cycle, etc., but also in awakening their interest in, and aiding them to grasp, the essential idea of the calculus.

The model described below is, of course, only one of many possible arrangements which are not difficult to invent on paper, but this one has the advantage of having been actually tried and used by students, and this seems a sufficient reason for publishing its description. It can be constructed with about a day's work by any amateur mechanic.

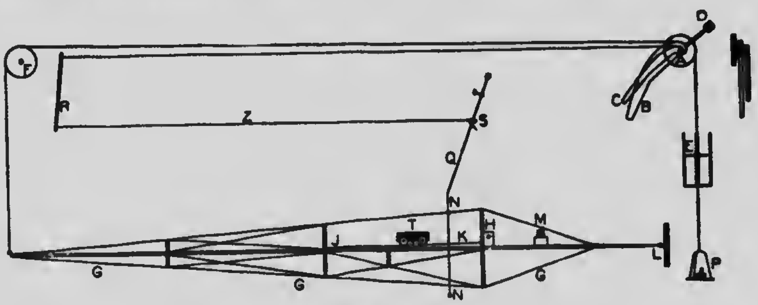

Fig. 1

It may be objected that the model is more complicated than the laws it is intended to elucidate. To this it may be answered that if it were *not* so the students would pass it over as lightly as they do the laws themselves.

The model is set up on the vacant wall of a laboratory where students may work with it without interference from instructors. The essential part of the apparatus is a circular wooden pulley A, 20 cm in diameter, to which is fixed rigidly a wooden curve B, the co-ordinates of which are given in Table I, and which, together with the second curve (mentioned below), is exactly counterbalanced by the weight D. The curves are made of 3/8-inch pine and carry double rows of ordinary pins on the edge which act as flanges. The whole is pivoted with brass bearings on a horizontal steel pin. At a suitable point on A is fixed an iron wire (No. 24, B. & S.) which carries a pan P at its lower end. A tin cross-piece is attached to the wire at a convenient height from the ground to represent a piston, behind which is a piece of cardboard bearing a diagram of a cylinder and a millimeter scale. To the right hand end of the curve B a piece of strong thread is fastened, which passes round the curve to a pulley F, similar to A, and thence downwards to the end of the lever G, pivoted at H. This lever is made of a strip of light wood, about 4 meters long, and is braced with wire, as shown in the diagram, and also in the horizontal plane. It is counterbalanced by the weight M and is strong enough to carry a 5 kg weight at T. This weight rests on a toy wagon which may be moved along a flat board between J and K. On the edge of this board, which is in such a position that the centre of gravity of the weight remains in a line with the end of the lever and the fulcrum, is pasted a millimeter scale, numbered from the fulcrum as zero.

The curve B fulfils the condition that the length of the perpendicular from the centre of revolution to the horizontal tangent is inversely proportional to the angle through which the curve is moved. It is part of an infinite spiral, and was obtained graphically as the envelope of a suitable number of tangents. The position of the bottom of the cylinder (vol. = 0) may be found by turning the curve to the position in which the y-axis (see table) is horizontal. This corresponds to the angle of revolution taken as zero, in drawing the curve. The distance of A from F, about 5 meters, is such that the thread remains practically horizontal.

This arrangement gives the relation between pressure, volume, and temperature,

$$pv = nRt.$$

The pressure in grams is the weight on the pan P, *plus* the weight of the pan which is 100 g. The volume is the distance of E from the bottom of the cylinder, and the absolute temperature is the distance, in millimeters, of a pointer at the centre of gravity of the wagon T from the fulcrum H. For the dimensions and weight given, the value of n is 0.000317 g-mol and the limits of volume are in the ratio of 1 to 5.

The work done in compressing the gas isothermally is equal to the work required to raise the weight T, and therefore the scale L (which is 1400 mm from the fulcrum) gives the value of const. log v + const. If d is the reading in centimeters on this scale,

$$\text{work} = 5000 \frac{t}{1400} d \text{ g-cm}.$$

The additional restriction imposed on the variability of p, v, and t for *adiabatic* changes is supplied by the following arrangement. To the wheel A is fixed a second curve C which fulfils the following condition :

$$s = \frac{\text{const}}{a^{k-1}},$$

where s is the horizontal movement of a tangential thread, a the angle of rotation, and k the ratio Cp/Cv.

If l is the length of the perpendicular from the centre of revolution to the horizontal tangent, then

$$l = \frac{ds}{da} = \text{const}' a^{-k},$$

and consequently it was possible to obtain this curve, graphically, exactly as in the case of the one already described. The co-ordinates of the curve for $k = 2$ are given in Table II.[1] The tangential thread[2] actuates the lever R and the pointer Q, made of a very light, thin glass tube properly counterbalanced, to the end of which is attached a plumb line N, N of fine cotton terminating in a small weight. Since R is at a distance of about five meters from C and Q, it is clear that the horizontal movements of the plumb line N represent the alteration of temperature for an adiabatic change of volume, v, or,

$$tv^{k-1} = \text{const.}$$

Since the pivot of Q is exactly over the zero of absolute temperature, H, the proper value may be given to the above constant for any adiabatic line by moving the connecting point S (a small piece of sheet rubber with a hole in it) up or down the glass pointer till N is opposite the pointer on the temperature wagon. To carry out an adiabatic expansion, therefore, it is simply necessary to set the pointer for the initial state by adjustment of the point S, and then to keep the temperature wagon opposite N during the alterations of pressure. It is necessary, of course, after setting up the model, to adjust the length of the fiber Z, so that at infinite volume the adiabatic pointer will be at zero. This can be done by adjusting the fiber to any length, taking two pairs of readings of temperature and volume, and calculating what correction in length will satisfy the above equation.

The co-ordinates of the curves B and C are given in the following tables. The values are expressed in centimeters. For both curves the centre of revolution is $x = 10$, $y = 12.5$ and the tangent for vol. $= 0$ is parallel to the y-axis.

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[1] The value 2 was chosen rather than an actual value for some known gas, both to simplify the calculations and also to avoid the extreme slenderness of the p, v-diagram of an actual Carnot's cycle.

[2] Owing to the necessary lightness of the pointer and plumb line, the "sag" even of the finest cotton introduces an error. For this reason fine glass fibers were used for working the adiabatic pointer and found quite satisfactory. They can be attached to pieces of cotton, at the two ends, by strips of gummed paper.

TABLE I. (Curve B)

x	*y*	*x*	*y*
10.8	8.7	4.5	17.7
10.0	8.45	5.4	19.4
9.1	8.4	6.7	21.0
8.15	8.5	8.5	22.4
7.25	8.75	11.1	23.7
6.40	9.2	14.0	24.5
5.5	9.95	18.1	24.9
4.8	10.9	23.3	24.3
4.25	11.9	30.0	22.2
3.9	13.0	38.5	17.5
3.8	14.3	49.5	8.4
4.0	16.0	57.5	0.0

TABLE II. (Curve C)

x	*y*	*x*	*y*
10.2	12.0	17.7	18.7
10.0	11.87	21.0	18.5
9.7	11.8	23.5	18.1
9.3	11.9	27.0	17.1
8.9	12.2	30.2	16.0
8.6	12.7	38.6	11.9
8.4	13.6	49.0	5.5
8.7	14.7	55.5	0.4
9.8	16.2	—	—
11.2	17.2	—	—
12.6	17.9	—	—
15.0	18.5	—	—

In conclusion, a few examples of the problems illustrated by the model may not be out of place.[1]

A Carnot's cycle process was carried out between the absolute temperatures 483° and 360°, and a number of points were plotted in pressure-volume co-ordinates on millimeter paper. The various areas were cut out, weighed, and compared with a square of paper of known size. The work gained during the cycle was calculated by the following methods:

[1] The numbers and calculations were supplied by two second year students, Messrs. T. B. Allen and R. A. Daly.

(1) Weight of area enclosed by the two isothermals and two adiabatics, 0.2320 g, corresponding to 1850 g-cm.

(2) Weights of areas representing work done during isothermal expansions at 483° and 360,°, respectively,
0.8965 g, corresponding to 7156 g-cm
and 0.6697 g, " " 5346 "
Difference .... 1810 g-cm.

(3) $$\frac{T' - T''}{T'} Q_1 = \frac{483 - 360}{483} 7156 = \ldots\ldots\ldots\ldots \quad 1822 \text{ g-cm.}$$

(4) $$0.000317\, R \left(483 \log_e \frac{28.0}{16.2} - 360 \log_e \frac{37.0}{21.4}\right) = 1636 \text{ g-cm.}$$

The work done during the isothermal expansion at 483°, calculated *directly* from *weight of wagon* (4855 g) × distance raised (determined from movement of pointer, 4.13 cm, on scale L in figure) was:

$$4855 \frac{483}{1400} \cdot 4.13 = 6916 \text{ g-cm (compare value above, 7156 g-cm.)}$$

The equality of the amounts of work done during the two adiabatic expansions is illustrated by the weights of the corresponding areas of paper:

0.3993 g and 0.4045 g.

The values of the constant R, calculated from various points, taken at random, from the above-mentioned curves, are

85310, 85190, 83710, 85150, 84740.

The constancy of pv^k is illustrated by the values calculated for three points on one of the adiabatics:

21250, 21100, 20820.

It will be noticed that the model is not perfect; but the same may be said of gases.

University of Toronto,
Chemical Laboratory,
April, 1904.