XIV.—"*Stepped*" Ignition.

By RICHARD VERNON WHEELER.

DURING researches on the electrical ignition of gases, W. M. Thornton has observed certain discontinuities, to which he has applied the term "steps," and on which he bases a theory regarding the manner in which the ignition of inflammable mixtures of gases in general is effected.

The steps were first recorded when determining the effect of change in the composition of mixtures of ethane and air on their ignition by condenser discharge sparks (*Proc. Roy. Soc.*, 1914, [A], **91**, 18). They are also stated by Thornton to occur when ignition is by the impulsive electrical discharge, either (1) when the proportions of a combustible gas (for example, methane) mixed with air are varied, the pressure being maintained constant (*Proc. Roy. Soc.*, 1916, [A], **92**, 388), or (2) with a given mixture of combustible gas and air when the pressure is varied (*Brit. Assoc.*, 1916, Section C; *Colliery Guardian*, 1916, **112**, 503).

Sastry (T., 1916, **109**, 523), working at the Home Office Experimental Station, was unable to confirm the former of the two observations respecting ignition by the impulsive electrical discharge in the case either of methane or of hydrogen.

The remarkable nature of Thornton's results, and the importance of the theories to which they lead, demands that anyone working on similar problems should carefully check them. This I have attempted to do in the case especially of mixtures of methane and air.

The steps observed by Thornton when the percentage of methane in air was varied and ignition was by the impulsive electrical discharge were ill-defined, and are stated to have occurred only when

the sparking electrodes were unclean. Their existence is therefore doubtful. Using a method of experiment apparently similar to Thornton's, I have been unable to detect any discontinuity, although the curve has been traced over a wide range half-a-dozen times or more. Incidentally, it may be stated that no discontinuity has been observed with mixtures of air with hydrogen or with any one of the gaseous paraffin hydrocarbons, the only gases with which experiments were made. An account of this work is reserved for a future communication.

FIG. 1.

I propose for the present to confine myself to an examination of the more striking discontinuities recorded by Thornton when a 9.5 per cent. mixture of methane and air was ignited at different pressures by the impulsive electrical discharge.

A curve representing the results of Thornton's experiments (*loc. cit.*) is shown in Fig. 1 (the curve on the right-hand side of the diagram). The "igniting-currents" recorded are those currents passing through the primary circuit of an induction coil which, when broken, gave secondary discharges just capable of igniting the mixture.

My own results are also shown in Fig. 1. The mixture of methane and air contained 9.51 per cent. of methane (by analysis) in the case of curves *A* and *B*, and 9.52 per cent. in the case of curve *C*. A different explosion-vessel was used for each curve, the spark-gaps of which differed slightly one from another, but were approximately 1 mm. in each case. Each curve is hyperbolic, and there is no sign of discontinuity.

It would seem, therefore, that the production of "stepped ignition," such as has been recorded by Thornton, requires some condition of experiment which I have been unable to reproduce—or have been careful to exclude. A detailed description of my experimental conditions is therefore given.

EXPERIMENTAL.

If the vibrating contact in the primary circuit of an induction coil is held closed and the circuit is suddenly broken, a single disruptive discharge takes place at a spark-gap in the secondary circuit. With a given spark-gap and a given rate of break of the primary circuit, the voltage of the secondary discharge is proportional to the primary current.

The relative ease of ignition of different gaseous mixtures, or of the same mixture at different pressures, can thus be measured by measuring the least current passing in the primary circuit of a given induction coil which, when broken at a constant rate, gives a discharge or "spark" at a fixed spark-gap just capable of igniting the mixtures.

It will be seen that to ensure truly relative results, it is essential (1) that the spark-gap in the explosion-vessel should be fixed and incapable of inadvertent or unobserved alteration, and (2) that no variation should occur in the rate of break of the primary circuit.

In Fig. 2 is shown the form of explosion vessel used for the experiments described in this paper. It consists of a globe of stout glass of about 75 c.c. capacity, with fixed electrodes of stout platinum wire fused in. The electrodes reach to the centre of the vessel, and are covered with glass to within 1 mm. of their ends, which are sharpened to fine points. A three-way tap serves to make connexion with (1) a gas-holder and mercury manometer, and (2) a vacuum pump.

Fig. 3 is a photograph of the arrangement for ensuring an unvarying rate of break of the primary circuit. The circuit is completed when the rod, *A*, touches the flat steel spring, *B*, remains established while the turntable revolves, and is suddenly broken

FIG. 3.

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as soon as the rod slips off the end of the spring. The turntable is driven by an electric motor geared down to a slow speed, so that a break of circuit in the primary of the induction coil occurs every two seconds. A condenser of 0.25 microfarad is placed across the break to minimise sparking at the contacts.

The coil used was an "8-inch" X-ray coil. Current was obtained from a battery of accumulators at 30 volts, and was measured (regulation being made by a sliding rheostat) with "Weston" ammeters.

The gas-mixtures were stored over glycerol and water in glass gas-holders, and were analysed before use. The same supply (containing 9.51 per cent. of methane) was used for the experiments

FIG. 2.

recorded in curves *A* and *B*; the supply used for curve *C* contained 9.52 per cent. of methane. The gas was prepared by purifying and liquefying firedamp, obtained, compressed in cylinders, from a coal mine in South Wales, and contained 99.8 per cent. of methane (*C/A* on explosion analysis 2.00).

As already stated, three different explosion vessels were used, one for each curve, the spark-gap in each case being about 1 mm.

The method of experiment was that of trial and error. The explosion-vessel was thoroughly exhausted of air, and some of the gas-mixture admitted until the pressure as read on the mercury manometer was that required. An arbitrary current was established in the primary circuit of the induction coil, and ten

secondary discharges passed at the spark-gap by setting the revolving contact in motion. If ignition did not take place before ten discharges had passed, the explosion-vessel was exhausted, a fresh charge of gas-mixture introduced, and a higher current tried; and so on, until the limiting current was fixed at each pressure within 0.01 ampere for currents below 3 amperes and within 0.1 ampere for currents above that figure.

Each point on each curve was checked three or four times, and no discrepancies were observed. At pressures as low as 50 mm. mercury it was difficult to decide by direct observation whether ignition took place or not, the glow of the discharge masking that of the ignited gases; a contraction in volume occurred at 50 mm. pressure (curve *A*) with an igniting-current of about 10 amperes.

My friend Mr. Allan Greenwell has been good enough to make a mathematical analysis of curve *A*, the results of which are as appended.

MATHEMATICAL.

(By ALLAN GREENWELL.)

The curve obtained by plotting igniting-currents as ordinates against pressures as abscissæ is remarkably smooth, and suggests that it follows a definite law.

Taking the experimental determinations at pressures of 1, 2, 3, 5, and 7 "hundred mm." of mercury as recorded by curve *A*, and assuming that the curve is a conic, the following empirical equation is obtained:

$$x^2 - 11.685x + 4.1867y^2 - 53.373y + 35.53xy - 77.865 = 0.$$

From this formula it can be shown that the transverse axis of the curve is inclined to the axis of abscissæ at an angle of $+47^\circ 33' 75''$. By rotating the axes of co-ordinates through this angle, so that they are brought into parallel with the axes of the curve, the equation becomes:

$$\left(\frac{x - 1.157}{2.132}\right)^2 - \left(\frac{y + 0.895}{2.496}\right)^2 = 1.$$

From this equation it is seen that the curve is a hyperbola, the semi-axes of which are 2.132 and 2.469 respectively, the centre being situated at the point $x = +1.157$, $y = -0.895$ referred to the new axes, or $x = +1.444$, $y = +0.2476$ referred to the original axes.

By calculation, the curve cuts the axis of abscissæ and the axis of ordinates at $x = +16.425$ and $y = +14.07$ respectively, and the transverse axis of the curve cuts the axis of abscissæ at $x = +1.2176$.

The following table gives the observed and calculated values of x and y :

Pressures. (Mm. of mercury). (x).	Relative igniting currents. (Amperes). (y).	
	Observed.	Calculated.
100	7.20	7.20
150	4.60	4.75
200	3.15	3.15
220	2.65	2.72
250	2.22	2.25
300	1.72	1.72
350	1.38	1.39
400	1.12	1.16
450	0.95	1.00
500	0.87	0.87
550	0.77	0.77
600	0.68	0.69
650	0.60	0.62
700	0.56	0.56
750	0.52	0.51

The fact of the hyperbola cutting the axes of co-ordinates has been very puzzling. Assuming that the experimental work is accurate, and that the numerical quantities represent the experimental determinations truly, that is to say, that they quantitatively represent, respectively, the igniting power of the current and the state of compression of the gaseous mixture at the exact moment and locus of ignition, then the curve cannot cut the axes. For there cannot be ignition at 0 mm. pressure, and at no pressure (under the conditions of the experiments) can the igniting current be less than zero.

The following argument is suggested as a clue to a possible explanation of the apparent anomaly. The curve is plotted to rectangular axes, which assumes that the quantities represented by measurements along the axes are absolutely independent of each other. The question is: Does this condition prevail in the present case?

(1) If the current (y) is increased without intentionally changing the pressure (x), a change of pressure may still take place, automatically, due to the energy of the spark.

(2) If the pressure is increased without intentionally changing the current, a change in the activity of the spark may take place due to a change in the resistance of the spark-gap, caused by the change of the density of the intervening medium.

In either of these hypothetical cases, the measurements to be represented by x and y would not be altogether independent of each other.

An inspection of the accompanying diagram (Fig. 4) will show

that, in order to prevent the curve cutting the axes of co-ordinates, these axes must be parallel to the asymptotes of the curve, and the curve must lie wholly within one "quadrant."

Using the same origin, but employing inclined axes parallel to the asymptotes of the hyperbola, then, considering any point on the curve, the new inclined ordinate (y') will represent the real igniting power compared with the old rectangular ordinate (y) which represents the recorded igniting current. In the same manner, the inclined abscissa (x') will show the real pressure compared with the recorded pressure (x).

FIG. 4.

Calculated points on the curve, where they differ appreciably from the observed points, are shown as crosses.

The relations between x' , y' , and x , y , are given by the following equations, where ϕ is the angle between the asymptotes and θ is the angle of inclination of the transverse axis of the hyperbola to the horizontal axis of abscissæ:

$$x' = [x - y \cot(\phi/2 + \theta)][\cos(\phi/2 - \theta) - \cot \phi \cdot \sin(\phi/2 - \theta)]$$

$$y' = [y + x \tan(\phi/2 - \theta)][\sin(\phi/2 + \theta) + \cot \phi \cdot \cos(\phi/2 + \theta)].$$

In the case under consideration, $\phi = 98^\circ 21' 68''$ and $\theta = 47^\circ 33' 75''$.

From these equations, the values of x' , y' have been calculated for the typical points on the curve, the rectangular co-ordinates of which were used for calculating the empirical equation of the curve:

(x).	(y).	(x').	(y').
1.0	7.20	1.86	7.30
2.0	3.15	2.38	3.24
3.0	1.72	3.21	1.82
5.0	0.87	5.12	1.02
7.0	0.56	7.09	0.76

The asymptotes of the hyperbola cut the inclined axes (OX' , OY') at distances from the origin equal respectively to

$$[p \sin(\phi/2 + \theta) - q \cos(\phi/2 + \theta)] \operatorname{cosec} \phi.$$

and

$$[p \sin(\phi/2 - \theta) + q \cos(\phi/2 - \theta)] \operatorname{cosec} \phi.$$

where p and q are the co-ordinates (rectangular axes) of the centre of the hyperbola. In the present case, $p=1.444$ and $q=0.2476$. Substituting numerical values, the expressions become respectively 1.479 and 0.2914. Then, taking the inclined co-ordinates of any point on the curve, and deducting from the abscissa the value 1.479, and from the ordinate the value 0.2914, and multiplying the differences, it is found that the product is always a constant and equal approximately to 2.66.

The value of the constant (2.66) is equal to $a^2 + b^2/4$, where a and b are respectively the semi-transverse and semi-conjugate axes of the hyperbola.

It should be borne in mind that, throughout the present investigation, the dimensions of the hyperbola have not been changed or its position with regard to the origin altered. The only variations that have been made have been in regard to the inclination of the axes of co-ordinates and their included angle.

The general conclusions suggested by this mathematical analysis of curve A are as follow:

(1) The quantities represented by the observations of the igniting-current and the degree of compression are mutually involved.

(2) The real quantities, as distinguished from the recorded quantities, may be represented by employing inclined axes parallel to the asymptotes of the hyperbola, the position of the origin remaining the same.

(3) The distance, parallel to the axis OX' , between the axis OY' and the relative asymptote represents the real value of the minimum pressure at which ignition can be obtained (under the experimental conditions) with any current. The distance, parallel

to the axis OY' , between the axis OX' and the relative asymptote represents the real value of the minimum current which can produce ignition (under the experimental conditions) with any degree of compression.

(4) The product obtained by multiplying the real value of the pressure less the minimum pressure by the real value of the igniting current less the minimum igniting current is constant.

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