VIII.—*The Inflammation of Mixtures of Ethane and Air in a Closed Vessel: The Effects of Turbulence.*

By RICHARD VERNON WHEELER.

WHEN describing the inflammation of mixtures of methane and air it was noted that the speed at which flame spreads through the mixture in a closed vessel is demonstrably dependent on the degree of mechanical agitation imparted to the mixture, as, indeed, is the speed of flame in all combustible mixtures and under all conditions other than those existing during the propagation of the explosion wave.

This important fact appears first to have been observed, or, at all events, first commented on by Schloësing and de Mondésir about the year 1864. Their experiments, which involved an extended study of the mode of propagation of flame, were carried out mainly with mixtures of carbon monoxide and air, and were undertaken in connexion with a research on the working of gas engines. Mallard and Le Chatelier, to whom the results of the experiments were communicated verbally, have thus described them (*Ann. des Mines*, 1883, [VIII], **4**, 298):

"Ces recherches ont mis en évidence un fait d'une grande importance, l'influence de l'agitation du mélange gazeux sur la vitesse de propagation de la flamme. Des mélanges très lents (et par cette expression nous entendrons ceux dans lesquels la vitesse de propagation est faible) peuvent donner lieu à des propagations pour ainsi dire instantanées, c'est-à-dire à de véritables explosions, quand on provoque au moment de l'inflammation une agitation intérieure très vive, telle que celle que l'on obtient en faisant déboucher au milieu d'une masse gazeuse en repos un jet de gaz animé d'une grande vitesse."

These observations appear to have been overlooked or forgotten until the subject of the agitation or turbulence of gaseous mixtures became of manifest importance during the investigation of gaseous explosions instituted by the British Association for the Advancement of Science. New experiments on the subject, by Dugald Clerk and Hopkinson, are recorded in the Fifth Report of the Committee on Gaseous Explosions (*Rep. Brit. Assoc.*, 1912, 201).

To quote from his Gustave Canet lecture (Junior Institution of Engineers, 1913), Dugald Clerk "had long ago observed that gas engines would have been impracticable had the rates of explosion been the same in actual engine cylinders as in closed-vessel experiments." During his experiments in 1912 he "found that the rate of explosion rise in the same engine varied with the rate of revolution, increasing with increased number of rotations per minute, and was due to the turbulence or eddying caused by the rush of gases into the cylinder during the suction stroke, which persisted during the compression stroke."

By drawing in a charge of mixture into the gas-engine cylinder in the ordinary way, and then tripping the valves and compressing and expanding the charge for one or two revolutions before igniting it, the turbulence was given time to die away. It was found that the effect of thus damping down turbulence was to retard the rate of inflammation of the mixture to a remarkable extent. For example, with a mixture of coal-gas and air containing about 9·7 per cent. of gas, ignition in a gas-engine cylinder under normal conditions at the end of the first compression stroke (the engine being run at 180 revolutions per minute) resulted in the maximum pressure being attained after 0·037 sec.; whilst when ignition was at the end of the third compression stroke, after the charge had been expanded twice and turbulence had subsided, the time taken for the attainment of maximum pressure was 0·092 sec.

Hopkinson experimented on the effects of turbulence at the same time as Dugald Clerk, using a cylindrical vessel 30·5 cm. in diameter and 30·5 cm. long. A small fan was mounted at the centre of the vessel, and comparison was made of the results of igniting similar mixtures with the fan at rest and in motion. With mixtures of coal-gas and air containing 10 per cent. of gas, the times that elapsed between ignition and the attainment of maximum pressure were: (1) with the fan at rest, 0·13 sec.; (2) with the fan running at 2,000 revolutions per min., 0·03 sec.; and (3) with the fan running at 4,500 revolutions per min., 0·02 sec.

Simultaneously with, and independently of, the experiments thus made on behalf of the Gaseous Explosions Committee of the British Association, a problem under investigation for the Explosions in Mines Committee of the Home Office was found to involve a study of the effects of turbulence on the inflammation of gaseous mixtures. The problem was to determine the effect, if any, of the presence of incombustible dusts in suspension on the limits of inflammability of mixtures of firedamp and air. A series of experiments on the ignition of mixtures near the lower limit of inflammability was made with a spherical vessel of about 4 litres capacity (described in T., 1918, **113**, 855) provided with a fan which could be rotated at a high speed so as to agitate the mixture and maintain dust in suspension. Naturally, the fan was rotated whether dust was present or absent, so as to ensure that the comparative experiments required should be made under as far as possible identical conditions. The pronounced effect of turbulence or agitation of a gaseous mixture on the speed at which flame travels through it thus became manifest, for many experiments had previously been made with similar mixtures in the same sphere without the fan.

The fan had four blades, and was attached to a horizontal shaft passing through an air-tight gland near the bottom of the sphere. Each blade extended for 7·5 cm. along the shaft and had a maximum width of 2·5 cm., the edge having a radius of curvature of 9·5 cm. The shaft was so fitted that there was a clearance of 1 cm. between the side of the sphere and the edges of the fan-blades. A slight helical twist was given to each blade.

Several experiments were made with mixtures of ethane and air near the lower-limit of inflammability, which, with ignition at the centre of a closed spherical vessel of glass of 2·5 litres capacity, is 3·10 per cent. ethane. With 3·0 per cent. of ethane flame travels slowly throughout nearly the whole of the (non-turbulent) mixture in such a vessel; and with 2·9 and 2·95 per cent. of ethane flame spreads through about one-third of the mixture (T., 1911, **99**, 2026). It will therefore be realised that even though a mixture may not contain sufficient ethane to ensure continued self-propagation of flame, part of the mixture may be burnt with a consequent development of pressure in a closed vessel.

The earlier experiments with turbulent mixtures were made with the fan running at 100 revolutions per second. The means of ignition was a secondary discharge (from a "10-inch" X-ray coil) across a spark-gap of 12 mm. at the centre of the sphere, produced by breaking a current of 10 amperes in the primary circuit of the coil, the trembler being locked. Such a discharge is more than adequate to ignite any inflammable mixture of ethane and air when the mixture is still, yet it was found that no ignition, or, rather, no propagation of flame, took place with a mixture of ethane and air containing as much as 3·2 per cent. of ethane when that mixture was agitated by the fan at 100 revolutions per second. On stopping the fan and allowing the turbulence to subside, ignition took place readily with complete inflammation of the mixture and the development of a pressure of 3·4 atmospheres.

Similarly, with mixtures containing 3·15 and 3·05 per cent. of ethane no ignition could be obtained, whilst the fan was running (at 100 revolutions per second), however frequently the discharge was passed, although when the mixtures were free from turbulence ignition occurred on the first passage of the discharge. Details of these and similar experiments are as follow:

Ethane in mixture. Per cent.	Result.
3·20	No ignition when the fan was running at 100 revolutions per sec. With the fan at 40 revolutions per sec. ignition took place, a pressure of 4·5 atm. being recorded 0·25 sec. after ignition. Without the fan running, a pressure of 3·4 atm. was developed.
3·15	No ignition could be obtained when the fan was running at 100 revolutions per sec. Without the fan, ignition occurred at once, a pressure of 3·2 atm. being recorded.
3·10	With the fan at 40 revolutions per sec. ignition occurred on the fourth passage of the discharge. With the fan at 20 revolutions per sec. ignition occurred at once. A pressure of 4·4 atm. was developed on both occasions, 0·177 sec. after ignition in the first experiment, and 0·287 sec. after ignition in the second.
3·05	No ignition could be obtained when the fan was running at 100 revolutions per sec. Without the fan, ignition occurred at once and a pressure of 2·8 atm. was recorded.
3·00	No ignition with the fan at 100 revolutions per sec. With 20 revolutions per sec. ignition occurred at once and a pressure of 4·3 atm. was recorded 0·30 sec. after ignition.
2·95	With the fan running at 20 revolutions per sec. ignition occurred when the discharge was maintained (the trembler of the coil being in action). A pressure of 4·2 atm. was recorded.

Strong agitation of a mixture poor in combustible gas renders it difficult to ignite, or, to be precise, renders it difficult for the flame that no doubt occurs during the passage of the discharge to spread away therefrom and travel throughout the mixture. This difficulty increases as the degree of agitation is increased and as the percentage of combustible gas is decreased. When, however, the flame in such an agitated mixture does manage to spread away from the source of ignition it travels rapidly.

From the high pressure developed when a mixture was ignited that contained 2·95 per cent. of ethane and to which turbulence had been imparted by a fan running at 20 revolutions per second, it seemed that flame must have travelled through a greater proportion of the mixture than the one-third observed when the mixture was quiescent. An apparatus was therefore devised to enable the appearance of the flames in turbulent mixtures to be examined. The apparatus, which consisted essentially of a globe of glass of about 4 litres capacity, is shown in Fig. 1, and needs no description. Preliminary experiments were made to determine the direction of the air-currents induced by the fan, which had two helical blades and revolved on a vertical axis. From the behaviour of coloured powders introduced into the globe while the fan was spinning it appeared that air was drawn from the centre of the globe towards the axis of the fan, and was discharged at the periphery of the latter as a spiral current directed obliquely * around the walls of the globe.

Mixtures of methane and air were used for the experiments. Normally, the lower-limit for central ignition of methane–air mixtures in a closed sphere is 5·6 per cent. methane; the flame travels upward from the spark at the centre until it occupies one-third of the vessel, when it travels downwards as a horizontal disk to the bottom. The appearance of the flames in mixtures containing less than 5·6 per cent. of methane is shown in Fig. 3, T., 1911, **99**, 2025.

When a 5·6 per cent. mixture of methane and air was agitated by spinning the fan at about 50 revolutions per second, a succession of discharges from an induction coil, the trembler of which was in operation in the usual manner, apparently failed to cause ignition. On close observation, however, it was seen that a pointed tongue of flame appeared at each passage of the discharge directed *downwards* towards the axis of the fan, apparently drawn thither by the current. The flame was about 2 cm. long and formed a sharp-pointed cone having the spark-gap (12 mm. in length) as its base. Occasionally, if the discharge were maintained, a fine filament of flame darted rapidly over a distance of a few cm. towards the fan. The speed of the fan was now reduced to about 30 revolutions per second and a discharge passed across the gap. The sequence of events was too rapid to be followed by the eye. It was observed that a downward-pointing tongue of flame was produced as before, and that this tongue, after some hesitation, shot towards the axis of the fan; the whole vessel then seemed to fill with flame and the glass was shattered into powder.

Further experiments were made with mixtures containing less methane. On two occasions the globe was shattered owing to the

* No doubt owing to an unequal setting of the blades of the fan.

rapidity with which the mixture contained in it was inflamed, but in a number of experiments, notably in several with a mixture containing 5·0 per cent. of methane (see T., 1914, **105**, 2595), the movement of the flame could be followed; or, at all events, owing to the persistence of retinal impressions, the course taken by the flame was apparent. An attempt has been made to indicate the appearance of the flame to the eye at a given instant by the shaded additions to Fig. 1. The impression produced can be described as that of a spiral whirlwind of flame, the axis of the spiral being inclined at an angle; in effect, the flame seemed to follow the course of the current induced by the fan. It appeared also that the flame passed several times through the mixture before it finally died away at the centre of the sphere. Analysis of the products of combustion of the 5·0 per cent. mixtures of methane and air showed that all the methane had been burnt.

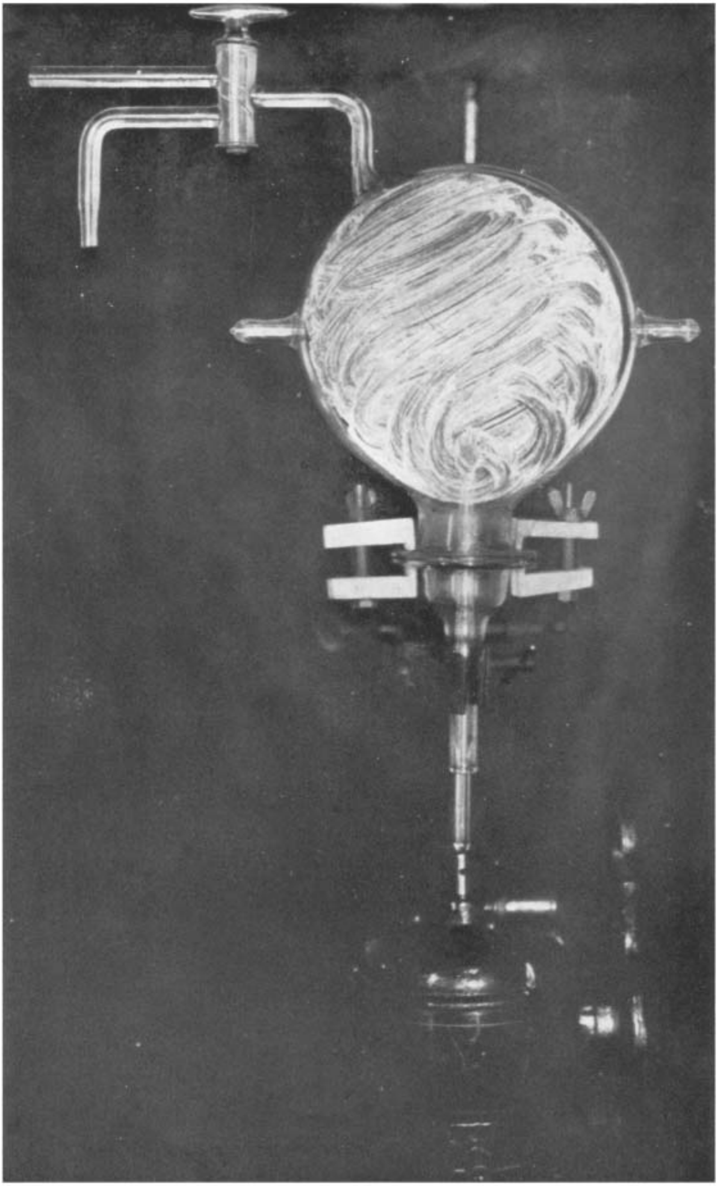
There can be little question, as a result of these observations, that the action of the form of turbulence studied in causing an enhanced speed of combustion of a weak inflammable mixture of methane or ethane and air within a closed vessel is purely mechanical. The flame, which normally would be propagated mainly by conduction of heat from a burning to an unburnt "layer" of mixture, is forcibly dragged in the wake of the rapid current induced by the fan, burning the mixture in its path. The difficulty experienced by the flame in such weak mixtures in travelling away from the source of ignition if the speed of the fan is very great is no doubt due to the fact that mixtures of the paraffins with air exhibit a considerable "time-lag" when the temperature of the source of heat that causes ignition is but little above the ignition-temperature, a condition obtaining with the flames of limit mixtures.

With richer mixtures, in which flame normally spreads at an equal speed in all directions from the source of ignition, the action of turbulence is mechanical also. To quote Mallard and Le Chatelier (*loc. cit.*, p. 350):

"Lorsque le gaz dans lequel progresse la flamme est à l'étât d'agitation, la vitesse de propagation augmente parceque la chaleur se transmet non seulement en vertu de la conductibilité du mélange gazeux, mais encore en vertu des différences de vitesse des diverses parties de la masse. La surface de la flamme, au lieu de garder une forme constante et régulière, se deforme à chaque instant, augmente de largeur en multipliant les points d'inflammation et, par suite, en rendant plus rapide la progression de la combustion."

If this explanation is correct, it follows that (1) the greater the turbulence the more rapid should be the combustion; and (2) a

FIG. 1



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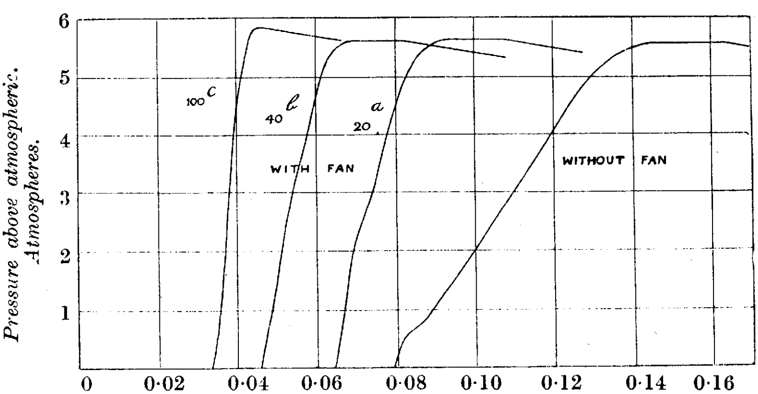
mixture in which the speed of flame normally is slow should be more susceptible to the effects of turbulence than one in which the speed of flame normally is rapid.

The first deduction has received experimental verification by Hopkinson, whose results have already been quoted. His results are confirmed by a series of experiments in the 4-litre sphere with mixtures of ethane and air containing 3·85 per cent. of ethane, the time-pressure curves for which are reproduced in Fig. 2. The time-intervals between ignition and the attainment of maximum pressure were: mixture at rest, 0·146 sec.; fan running at (*a*) 20 revs. per sec., 0·091; (*b*) 40 revs. per sec., 0·070 sec.; (*c*) 100 revs. per sec., 0·045 sec. Additional points that should be

FIG. 2.



Time, seconds. Time 0 = time of ignition.

noted as regards these curves are: (1) the slight increase of pressure obtained with the turbulent mixtures (*a*) and (*b*), and the marked increase with the turbulent mixture (*c*) as compared with that produced by the quiescent mixture; and (2) the disappearance from the curve for turbulent mixture (*c*) of the horizontal portion at maximum pressure noticeable in the other three curves. An explanation of these effects is offered later.

In order to test the second deduction that should follow if the explanation suggested for the action of turbulence is correct, two series of experiments were made with mixtures of ethane and air ranging between the lower-limit mixture and that giving the maximum pressure on combustion. In the one series the fan was run at a constant speed of 100 revolutions per second; in the other the fan was at rest. The time–pressure curves for typical experiments of these two series are shown in Figs. 3 and 4,* the curves for the

FIG. 3.

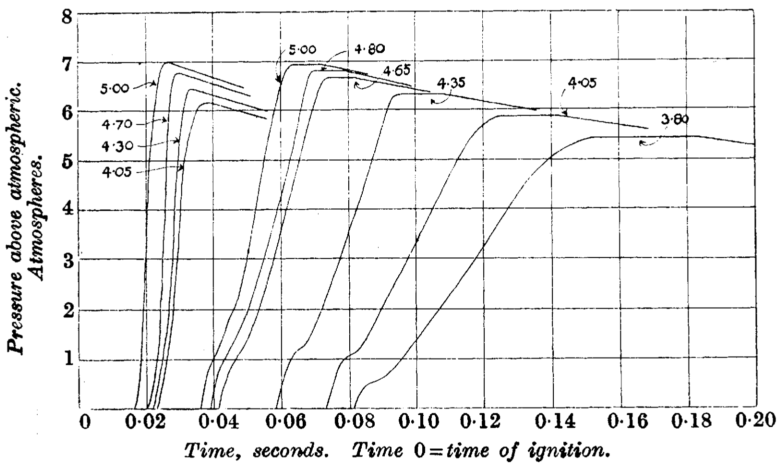
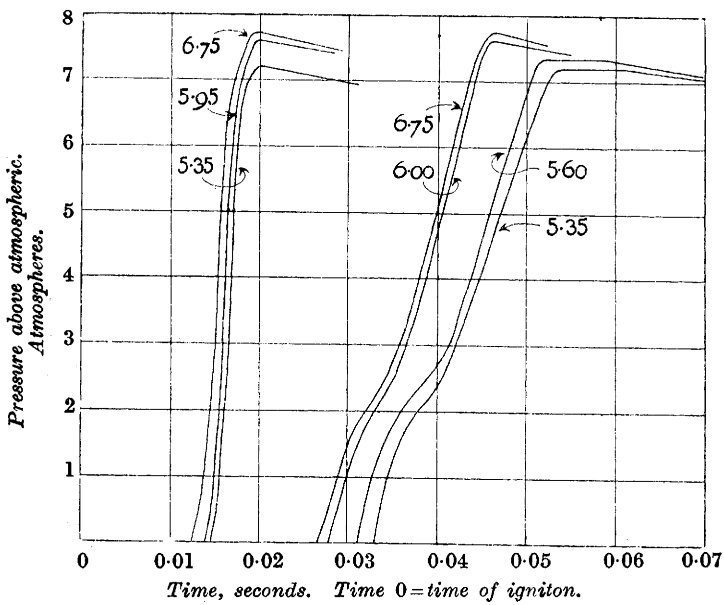


FIG. 4.



* It should be noted that the unit of time employed in plotting the curves in Fig. 3 (and Fig. 2) is double that in Fig. 4. This contraction of the time-scale is rendered necessary from considerations of space.

turbulent mixtures occupying the left-hand portion of each diagram.

From these curves the time that elapsed between ignition and the attainment of maximum pressure for each mixture can be determined. These times, together with the times for mixtures not included in Figs. 3 and 4, are recorded in the table that follows:

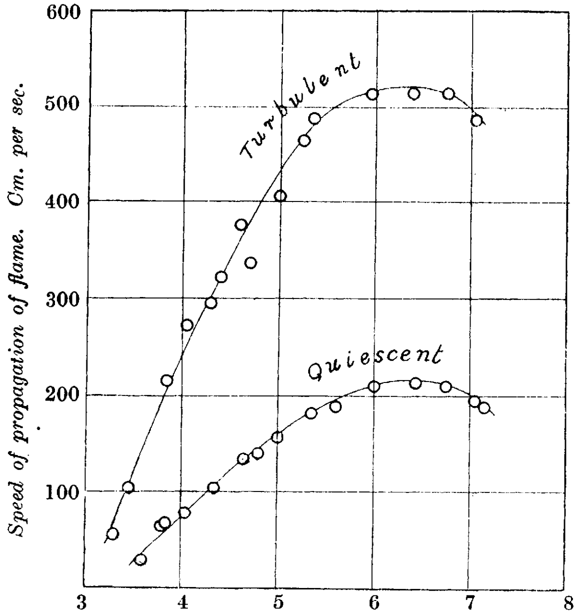
Ethane in mixture. Per cent.	Time between ignition and the attainment of maximum pressure. Seconds.	
	Without turbulence.	With turbulence.
3·30	—	0·176
3·45	—	0·096
3·60	0·332	—
3·80	0·152	—
3·85	0·146	0·045
4·05	0·124	0·036
4·30	—	0·033
4·35	0·094	—
4·60	—	0·026
4·65	0·073	—
4·70	—	0·029
4·80	0·070	—
5·00	0·063	0·024
5·25	—	0·021
5·35	0·054	0·020
5·60	0·052	—
5·95	—	0·019
6·00	0·0465	—
6·40	—	0·019
6·45	0·046	—
6·75	0·0465	0·019
7·05	0·050	0·020
7·15	0·052	—

It has been shown (T., 1918, **113**, 852) that these time-intervals can be used to calculate, for each mixture, the mean speed of propagation of flame between the centre and the top of the sphere, a distance of 9·75 cm. The speeds thus calculated are shown plotted against percentages of ethane in Fig. 5. Allowing for the irregularities, which are naturally more noticeable with the turbulent than with the quiescent mixtures, the speeds for equivalent percentages of ethane in the two sets of experiments, as deduced from the smoothed curves, are given in the table on p. 90.

The conclusion that a mixture in which normally the speed of flame is slow should be affected by turbulence to a greater extent than one in which normally the speed of flame is rapid is thus proved experimentally by the gradual diminution in the value of the ratio B/A.

The Development of Pressure.—On referring to the time–pressure curves for mixtures without turbulence given in Figs. 3 and 4, and

FIG. 5.



comparing them with the curves for mixtures of methane and air previously published (*loc. cit.*, Fig. 2, p. 847), it will be seen that

Mean Speed of Propagation of Flame from Centre to Top of Sphere. Cm. per sec.

Ethane in mixture. Per cent.	Without turbulence. (*A*).	With turbulence. (*B*).	Ratio *B*/*A*.
3·6	35	142	4·06
3·8	55	195	3·54
4·0	75	237	3·17
4·2	95	284	2·99
4·4	112	320	2·85
4·6	129	360	2·79
4·8	144	400	2·77
5·0	158	430	2·72
5·2	172	462	2·68
5·4	185	485	2·62
5·6	195	500	2·56
5·8	202	510	2·52
6·0	210	518	2·47
6·5	212	518	2·44
6·7	200	495	2·47

both sets of curves are of the same type. All the mixtures of ethane and air up to and including that containing 5·6 per cent. of ethane have time–pressure curves which exhibit the three stages of development noticeable with the mixtures of methane and air. The explanation of these stages offered when describing the methane curves can be applied also in the present instance.

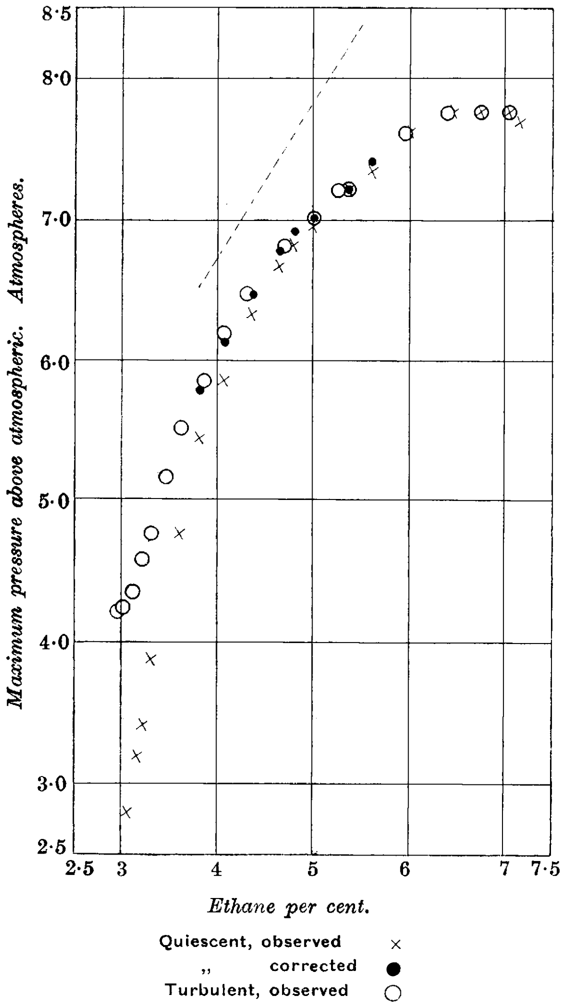
Support is given to the assumption then made that the second stage of development, during which the recorded pressure remains constant, represents a balance between a gradual decrease of pressure that begins as soon as inflammation of the mixture is complete and is due to cooling by the walls of the vessel, and an increase of pressure incident at the same moment and due to the gradual attainment of thermal equilibrium. For it will be found that a graphical "correction" applied, in conformity with this assumption, in the manner described (*loc. cit.*, p. 849) yields results for the maximum pressures in close agreement with the maxima recorded by equivalent mixtures when turbulent, over the whole range from 3·80 per cent. ethane (at and above which percentage the flame travels from the centre in all directions at the same speed) upwards.

This is best shown in Fig. 6, where the observed maximum pressures for all the mixtures experimented with, both turbulent and quiescent, and the "corrected" maxima for the latter, are shown plotted against percentages of ethane. It should be observed that the magnitude of the correction, as is to be expected, diminishes in proportion as the speed of inflammation of the mixture increases. Similarly, the magnitude of the difference between the maximum pressures recorded with like mixtures when turbulent and quiescent also decreases as the speed of inflammation of the latter increases, until with mixtures containing more than 5·6 per cent. of ethane no difference is observable between the two sets of pressures. Further, the crests of the time–pressure curves for the quiescent mixtures that contain more than 5·6 per cent. of ethane no longer remain horizontal over a measurable length of time, but the cooling curves begin as soon as the maxima are attained.

Pier (*Zeitsch. Elektrochem.*, 1909, **15**, 536), who used the pressures developed by the inflammation of different mixtures in a closed vessel to determine the specific heats of various gases, has made observations which have a bearing on the question of the effects of turbulence.

Using a manometer of similar construction to the Petavel gauge (*Phil. Mag.*, 1902, [vi], **3**, 461), Pier found exact agreement between the observed and the calculated pressures produced by mixtures the combustion-temperatures of which exceeded 1600°. For this reason he combatted Nagel's opinion ("Versuche über Zundgeschwindigheit explosibler Gasgemische," *Mitteilungen über Forschungsarbeiten des Ingenieurwesens*, Vol. 54, 1908) that with central ignition in a spherical vessel the mixture near the walls must be raised in temperature by adiabatic compression before flame reaches it

FIG. 6.



(an opinion that had already received experimental verification by Hopkinson), and suggested that the interchange of heat between different portions of the mixture within the vessel must be practically instantaneous.

This result Pier supposed would be effected by a rapid whirling and mixing of the contents of a spherical vessel owing to a sudden increase of pressure on ignition at the centre. It is clear, if only by reason of the difference observable in the character of the time–pressure curves for ethane–air mixtures with and without artificially-produced turbulence, that Pier's contention cannot be correct; and Hopkinson's measurements of the temperatures within a closed cylindrical vessel at the moment of maximum pressure produced by the inflammation of a mixture of coal-gas and air (*Proc. Roy. Soc.*, 1906, [*A*], **77**, 387) should have convinced Pier of its falsity.

In the absence of knowledge regarding the composition of the products of combustion at the moment of attainment of maximum pressure when the ethane–air mixtures contain excess of ethane, it is not possible to calculate the theoretical pressures that should be given by such mixtures on ignition in a closed sphere were there no loss of heat during the propagation of flame. Calculation can, however, be made for those mixtures in which the combustion of ethane can be presumed to be complete. The mixture of ethane with air in which ethane and oxygen are in the theoretical proportions for complete combustion to form carbon dioxide and steam contains 5·63 per cent. of ethane. The dotted line in Fig. 6 represents the calculated maximum pressures over the range 3·8—5·5 per cent. ethane.* It will be seen that a loss of heat of between 9 and 12 per cent., presumably due to radiation during the propagation of flame, is indicated.

A matter for further study is the fact that the mixtures of ethane and air which produce the highest pressures are not those within close range of the mixture containing ethane and oxygen in theoretical proportions for complete combustion (5·63 per cent. of ethane), but lie over a considerably higher range, namely, 6·5—7·0 per cent. The time taken for the attainment of maximum pressure reaches a minimum over the same range, or, in other words, the speed of propagation of flame under the conditions of the experiments is fastest in mixtures containing between 6·5 and 7·0 per cent. of ethane. In this respect the results obtained with mixtures of ethane and air differ markedly from those with methane and air.

Further comparison of these results with those obtained with mixtures of methane and air is reserved for a future communication, which will include the results of similar experiments with other members of the paraffin series of hydrocarbons.

* The calculations were made in the manner described in T., 1918, **113**, 858, using Langen's values for the specific heats of the gases.

EXPERIMENTAL.

The apparatus used (4-litre sphere) and general method of procedure for the experiments has already been described (*loc. cit.*, p. 854). The ehane was prepared by the action of water on zinc ethyl and was purified by liquefaction by liquid air; the ratio *C*/*A* on explosion analysis was 1·25, showing that it contained no impurity.

The majority of the experiments described in this paper were carried out during the year 1912, with the assistance of Mr. M. J. Burgess.

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