LVI.—*The Propagation of Flame through Tubes of Small Diameter.*

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It has been shown in a previous communication (T., 1917, 111, 1044) that the speed of the "uniform movement" of flame in a given mixture of methane and air is dependent on the diameter of the tube along which the flame travels, being enhanced by the action of convection currents in tubes of large diameter and reduced by conduction of heat by the walls in tubes of small diameter.

If the diameter of the tube is sufficiently small, the "uniform movement" of flame does not develop, but the flame dies out after travelling a few centimetres. Still further reduction in the diameter of the tube renders it impossible for the flame to spread

any measurable distance from the point of ignition. This fact was discovered by Davy, and was the starting point of his researches on the construction of a safe lamp for use in coal mines, his observation being: "I found that in tubes of 1/7-inch in diameter explosive mixtures"—of firedamp and air—"could not be fired when they were opened in the atmosphere" ("Collected Works," Vol. 6, p. 11).

Schloësing and de Mondésir (quoted by St. Claire Deville, "Leçon sur la Dissociation," p. 46) and Mallard and Le Chatelier (*Ann. des Mines*, 1883, [viii], 4, 319) experimented on this subject, and the last-named have placed on record the speeds of flame in a mixture of methane and air containing 10·4 per cent. of methane, using tubes of glass of different diameters, as follow:

Diameter of tube, mm.	3·2	5·5	8·0	9·5	12·2
Speed of flame, cm. per sec....	nil	22	39	41	47

The methane used by Mallard and Le Chatelier was prepared from sodium acetate, and was impure; nevertheless, their observation that flame would not propagate in glass tubes of 3·2 mm. internal diameter is in fair agreement with Davy's statement (one-seventh of an inch is equal to 3·63 mm.).

Following on his discovery that a tube of small diameter would not allow flame to pass through it, Davy experimented with other means of exposing a cooling surface to the flame, such as perforated plates and systems of concentric tubes, and finally produced his wire gauze safety-lamp. A history of the development of the miners' flame lamp from Davy's original design would be out of place here, but it may be said that the retention of the wire gauze to protect the oil- or spirit-flame from inflammable mixtures of firedamp and air seems to have been regarded as essential by the majority of inventors. A few types of lamps have been constructed in which metal plates perforated with fine holes have been used, but no systematic experiments seem to have been recorded, on the lines of Davy's earlier experiments, to determine under what conditions tubes or perforated plates can be regarded as equivalent in safety to the gauze adopted, mainly for its convenience, by Davy.

In connexion with work on the construction of miners' safety-lamps, we have made a number of experiments on the speed of the uniform movement during the propagation of flame in mixtures of methane (firedamp) and air through tubes of small diameter; * on the passage of flame through similar tubes filled with mixtures

* It should be remembered that the uniform movement of flame is developed only when the inflammable mixture is contained in a tube closed at one end and open at the other, ignition being effected at or near the open end.

of methane and air and open at both ends; and on the passage or projection of flame through short tubes of small diameter.

The first series of experiments—on the uniform movement of flame—serves to demonstrate the increased cooling effect of the walls of the tube as its diameter is decreased, and may be regarded as an extension of the work already referred to (*loc. cit.*, p. 1050). The main results are shown in the table on p. 659; the numbers within brackets record distances, in cm., travelled by the flames before they became extinguished; the other numbers record the speeds of the flames in cm. per second, propagation taking place throughout the lengths of the tubes; the word nil indicates that flame could not be seen to spread an appreciable distance from the secondary discharge spark used to cause ignition. Ignition was, in each instance, at a point 3 cm. from the open end of the tube; the flame was allowed to travel 30 cm. from the point of ignition and its speed over a distance of 1 metre then measured; the tubes were 3 metres in length. Each recorded result is the mean of three or four closely agreeing determinations.

There are several points of interest in this table. The apparent limits of inflammability (horizontal propagation of flame) are narrowed as the diameter of the tube is decreased until with a tube 4.5 mm. in diameter only one of the mixtures tested (containing 9.95 per cent. of methane) would propagate flame.

No attempt was made to determine for each tube the exact limiting percentages of methane required for propagation of flame, but the table should supply fairly close approximations. Thus, the tube 5.6 mm. in diameter would have as its lower limit mixture one containing less than 8.5, but more than 8.25 per cent. of methane, and as its higher limit mixture one containing more than 10.5, but less than 10.65 per cent. Bearing in mind the fact that the exact limiting mixtures were not obtained, it will be seen that the speeds of the flames tend towards a constant value of about 35 cm. per sec. as the limiting mixtures are approached. This speed can be regarded as the slowest at which continued propagation of flame in mixtures of methane and air is possible.

It follows that the higher the coefficient of conductivity of the material of which tubes of small diameter are made, the narrower are the limits of inflammability for a tube of given diameter and the larger is the diameter of tube capable of preventing the spread of flame in any mixture. Thus Davy (*loc. cit.*) found that "metallic tubes prevented explosion better than glass tubes."

In Fig. 1 a curve is given showing the relationship between the speed of the uniform movement in a 9.95 per cent. methane-air mixture and the diameter of the tube (of glass) along which the

Internal diameter of tube. Mm.	Methane in mixture. Per cent.																
	7.6	8.0	8.25	8.4	8.5	9.0	9.5	9.95	10.15	10.5	10.65	10.8	11.0	11.5	11.6	11.65	12.0
3.6	nil	nil	nil	nil	nil	nil	nil	nil*	nil	nil	nil	nil	nil	nil	nil	nil	nil
4.5	nil	nil	(20)	(18)	(20)	(20)	(20)	33.5	nil	nil	nil	nil	nil	nil	nil	nil	nil
5.6	(25)	(20)	(27)	—	36.3	38.4	40.8	41.2	40.8	38.4	nil†	nil†	nil	nil	nil	nil	nil
7.2	(37)	(30)	(30)	(30)	38.0	40.5	46.8	46.3	44.5	42.9	(60)	(53)	(43)	nil†	nil†	nil†	nil
8.1	(45)	(30)	(35)	36.5	39.3	42.4	47.7	47.4	46.7	44.0	42.2	41.0	(45)	(50)	—	—	(60)
9.0	(55)	32.6	34.8	—	40.4	44.4	48.9	48.0	47.9	46.5	45.5	—	42.5 ¹	36.9	35.5	(60)	(60)

* When the flame was started in a tube 5.6 mm. in diameter and 8 cm. long it travelled 30 cm. along the 3.6 mm. tube and then died out.

† Flame travelled towards the open end of the tube, a distance of 3 cm.

flame travelled. This curve is a continuation of that shown in Fig. 4 in T., 1917, 111, 1053, and should be compared therewith.

The Passage of Flame through Tubes Open at Both Ends.—When a mixture of methane and air contained in a horizontal tube open at both ends is ignited near one end of the tube, flame begins to travel with increasing speed towards the other end.* After a certain distance of travel, the flame vibrates backward and for-

FIG 1.

ward, and, in tubes of small diameter, becomes extinguished during any particularly rapid vibration. The distance travelled by the flame before vibrations begin depends on the length and diameter of the tube and on the percentage of methane in the mixture, being greater the longer is the tube and the larger its diameter, and less the nearer the percentage of methane approaches that required to give the fastest speed of flame (9.5 to 10 per cent. of methane in air).

* Unless the mixture is a "limit mixture," when the speed of the flame is uniform throughout its progress.

It thus results that a length of tube of diameter small enough to prevent the passage of flame in a mixture containing, say, 10 per cent. of methane in air, may fail to do so when the mixture contains only, say, 7 per cent., despite the fact that the flame in the former mixture has the greater speed. For the reason that with the 10 per cent. mixture vibrations, engendered by the rapidity with which the flame begins to move, may cause self-extinction of the flame, whilst with the 7 per cent. mixture the flame may move comparatively slowly and undisturbed throughout its course.

This fact is illustrated in the series of experiments recorded in the table that follows. The tubes were of glass and were 100 cm. long:

Percentage of methane in mixture	Distances travelled by flame in tubes open at both ends.		
	10.0	8.5	7.5
Internal diameter of tube.			
3.6 mm.	nil.	nil.	nil.
4.4 „	11.5 cm.	10 cm.	7.5 cm.
6.4 „	14	25 to 30	15 to 20
7.2 „	20 to 25	throughout	throughout.

Experiments of a similar nature were made with tubes of brass. The brass tubes were used as connexions between two open glass tubes 2.5 cm. in diameter and 10 cm. long, as described in the experimental portion of this paper, and their lengths were gradually shortened until flame passed from one glass tube to the other, when a mixture of methane and air was ignited near the open end of one of them. Two series of experiments were made; in one the propagation of flame was horizontal, in the other from below upwards. The results can be tabulated as shown on p. 661.

The lengths of brass tube recorded in this table represent relative distances of travel of the flames, the actual distances travelled being from 1 to 1.5 cm. less in each instance. The results for horizontal propagation of flame are shown graphically in Fig. 2, from which the greater precautions necessary to prevent the passage of flame in mixtures containing the lower percentages of methane is apparent.

The conditions under which an inflammation of firedamp takes place within a miners' safety-lamp depend on the construction of the lamp and on the manner in which it is manipulated. With some types of lamps (those receiving their air-supply from below the wick), the conditions are similar to those obtaining in the experiments just described. With others—and these constitute the majority of types—the air-supply reaches the wick from above, so that when firedamp is present in the air an inflammable mixture may occupy most of the upper portion of the lamp before it becomes

Percentage of methane in mixture.	Lengths of brass tube required to prevent the passage of flame. Cm.					
	10.0		8.5		7.5	
Internal diameter of tube. Mm. 3	Horizontal propagation.	Upward propagation.	Horizontal propagation.	Upward propagation.	Horizontal propagation.	Upward propagation.
	less than 2	less than 2	less than 2	less than 2	less than 2	less than 2
	4 to 5	5 to 6	2 to 3	5	less than 2	less than 2
	7.5	9	4 to 5	7.5	less than 2	less than 2
	10	11.5 to 12.5	11.5	18 to 19	30	30
	14	15 to 16	42 to 43	50	—	—
	16	18	54	55	—	—
29	32	more than 60	more than 60	—	—	

ignited. Ignition is then as if near the closed end of a tube open at the other end.

Experiments were made in which a glass tube 12 cm. long and 2 cm. in diameter, closed at one end, was used as an explosion-vessel. Brass tubing of different diameters could be attached to the open end and determinations made of the lengths required to prevent the transmission of flame to an inflammable mixture of methane and air when a similar mixture was ignited by a secondary discharge 15 mm. from the closed end of the explosion-vessel, the apparatus being fixed horizontally.

FIG. 2.

With mixtures of methane and air containing either 10 or 7.5 per cent. of methane, the passage of flame from the explosion-vessel to the atmosphere outside was prevented by less than 2 cm. length of brass tubing of any diameter up to the largest tried, namely, 8 mm. In many instances, tongues of slightly luminous gases were projected from the ends of the brass tubes, but inflammation of the surrounding mixture did not follow. The question therefore arose whether increasing the speed of projection of these hot gases, by increasing the length of the explosion-vessel, would enable them to retain sufficient heat to ignite a mixture of methane

and air even after their passage through a considerable length of brass tubing of small diameter.

Experiments were therefore made in which explosion-vessels, 2 cm. in diameter, of different lengths were employed, so that the flames in 10 per cent. mixtures of methane and air, ignited at the closed ends of the explosion-vessels, would acquire different speeds by the time they reached the open ends. Previous experiments had shown that the speed of flame in a 10 per cent. mixture of methane and air contained in a horizontal glass tube 2 cm. in diameter, closed at one end and open at the other, increases progressively with its distance of travel from the closed end over distances of 3 or 4 metres. The results were as follow:

Length of explosion-vessel. Cm.	Length of brass tube required to prevent passage of flame in a 10 per cent. methane-air mixture. Cm.			
	12	20	30	40
Internal diameter of brass tube. Mm.				
4	less than 2	less than 2	less than 2	3 to 4
4.4	"	3 to 4	"	3 to 4
4.8	"	13 to 14	16 to 18	more than 30
5.6	"	16 to 18	24 to 25	"
6.4	"	18 to 19	more than 30	"
7.2	"	19 to 20	"	"
8.0	"	19 to 20	"	"

The increased speed imparted to the heated products of combustion by increasing the speed of the flame thus materially reduces the protection against inflammation of the external atmosphere afforded by brass tubes. A miners' safety-lamp, however, rarely has an effective length of "explosion-vessel" exceeding 12 to 15 cm. On the other hand, its diameter is often as great as 6 cm. It seemed possible that the use of an explosion-vessel of larger diameter than that employed in the series of experiments just described might have an effect similar to increasing its length, inasmuch as the higher pressures produced within a vessel of greater capacity would project the heated products of combustion through the brass tubes with greater speed.

On trial, however, this was found not to be so. An explosion-vessel 7.5 cm. in diameter and 12 cm. long was no more effective in transmitting inflammation through brass tubes to the external atmosphere than one 2 cm. in diameter. Furthermore, when the length of this larger explosion-vessel was increased to 40 cm., it was found that protection was still afforded by a length of brass tube of less than 2 cm. of any diameter up to 8 mm., the largest tried. Increasing the capacity of the explosion-vessel thus actually

decreased the danger of the inflammation being conveyed to the external atmosphere.

These results, which were repeated many times with mixtures of different methane-content, are in conformity with some remarkable experiments by Beyling ("Verein für die Bergbaulichen Interessen im oberbergamtbezirk Dortmund." Essen, 1906), made primarily to determine the best means of rendering electrical machinery flame-proof. Beyling used an explosion-vessel 33.5 cm. in diameter and 42.5 cm. long (capacity, 42 litres), and found that when a mixture of firedamp and air containing 9 per cent. of methane was ignited at one end of the vessel, a hole more than 4 cm. in diameter could exist at the other end without danger of a similar mixture outside being ignited.

The explanation of these results is that the products of combustion, being under a fairly high pressure within the explosion-vessels of large capacity, were rapidly expanded as they issued

FIG. 3.

through the holes or tubes, and were thus cooled below the temperature at which they could ignite the mixture outside.

EXPERIMENTAL.

The experimental work can be divided into two portions, that dealing with the speed of flame in tubes of small diameter, and that relating to the passage of flame through short lengths of such tubes from vessels filled with inflammable mixtures.

The motion of the most rapid flame studied was sufficiently slow to follow by eye, so that for the measurements of speeds it sufficed to record the times at which the flames made their appearance at fixed points along the tubes. This was done by the use of a tapping-key in electrical connexion with a chronograph.

The different forms of apparatus used in the experiments on the passage of flame through short lengths of tubes are shown in Fig. 3. The upper diagram illustrates the means employed to study the passage of flame through tubes open at both ends. The ground-

glass cover, *A*, was removed just before igniting the mixture by sliding it downwards, so as to avoid disturbance of the mixture within the tube. The whole apparatus, including the glass extension beyond the length of brass tube undergoing test, was filled with the requisite mixture by displacement of air, six times the volume of the apparatus being taken for displacement.

The lower diagram shows the arrangement when testing the conditions necessary for the passage of flame from a closed vessel, and is self-explanatory.

The methane used throughout the experiments was from fire-damp obtained from a blower in South Wales; it contained 2 per cent. of nitrogen as its only impurity. The mixtures were stored over water in metal or glass gas-holders of suitable capacity, and were analysed before use.

These experiments have been carried out for the Mines Department of the Home Office. They complete part of a research on miners' safety-lamps which will form the subject of an official report.

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