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By J. M. Singer, A. E. Bruszak, and J. Grumer

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LIMITS OF FLAME PROPAGATION OF COAL DUST-METHANE-AIR MIXTURES

by

J. M. Singer,[1] A. E. Bruszak,[2] and J. Grumer[3]

ABSTRACT

Flame propagation of lower limit hybrid coal dust-methane-air mixtures in vertical and horizontal flame ducts of 15.2 cm id and 1.8 m length has been investigated to provide information bearing on safety in mines. Fuel concentrations at lower limits of flame propagation and equivalences of coal dust and methane are much higher for continuing flame propagation than for short-span flame propagation in the vicinity of an "overdriving" ignition source. As the energy of the ignition source was increased, the flame speed and the distance of flame propagation from the ignition source increased, whereas the total fuel concentration at the lower limit decreased.

INTRODUCTION

The present investigation of flames of fuel-lean hybrid coal dust-methane-air mixtures propagating downward or horizontally in ducts is part of a broad study by the Bureau of Mines of flammability of coal dust-bearing mine atmospheres. Laboratory models of actual coal mine situations are being used to obtain more reliable and less expensive information than could be obtained in large test galleries or coal mines. Earlier phases of this study dealt with minimum concentrations of dust and methane ignited by hot gas jets (2, 4);[4] quenching distances of flames of lower limit hybrid mixtures (3); equivalences[5] of coal dust and methane at the lower ignition limit (4) and at quenching (3); and incendivity of hot gases containing sodium salts (5).

The present study established equivalences, concentrations, and flame speeds of coal dust and methane at lower limits of non-steady-state flame propagation, for flames propagating to short distances from the ignition source and to distances long enough for the flame to escape the circumstances

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[4]Underlined numbers in parentheses refer to the references at end of report.
[5]Equivalance of coal dust to methane is defined as $\Delta c/\Delta m$, where c is the coal dust concentration and m is the methane concentration, each in mg/liter.

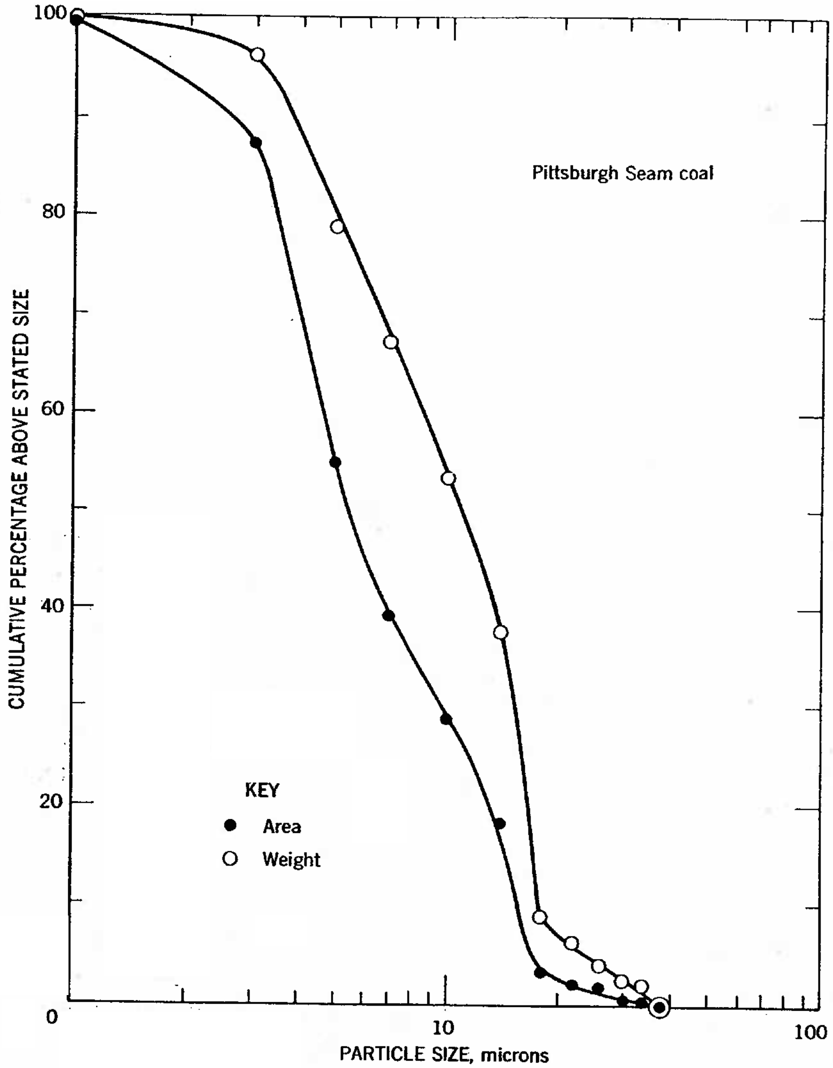


FIGURE 1. - Distribution of Coal Dust Particle Sizes.

of its ignition. The ignition sources were hot gas jets with more energy than the minimum required for ignition ("overdriven" ignitions). Such "overdriven" combustion of coal dust-methane-air may occur in the vicinity of high explosives shots in coal mines. Such information should be useful in improving safety in coal mines and for understanding the mechanism of ignition and combustion of dust clouds.

EXPERIMENTAL EQUIPMENT

The experiments were conducted with hybrid mixtures of methane and Pittsburgh Seam (Mathies mine) coal dust.[6] The particle size distribution of the dust (fig. 1) was determined by the optical microscope technique recommended by Drinker and Hatch (1). The methane gas was chemically pure grade.

The vertical and horizontal cylindrical flame ducts (15.2 cm id by 1.8 m long) were equipped with flame-detector photocells located 40.6 cm apart (fig. 2). Flow speeds of the hybrid mixtures through the vertical and horizontal ducts were 6.6 and 16.5 cm/sec respectively in a countercurrent direction to the direction of flame propagation.

The disperser (see fig. 2) was batch fed with coal dust that had been dried for 2 hours at 105° C in a nitrogen atmosphere. An airstream, injected with a hypodermic needle lifted the dust from the bottom of the rotating cup. A scraper blade leveled the dust layer so as to produce uniform dust concentrations. Not all the air was added through the hypodermic needle. The balance required to make a total flow of approximately 1,200 cu cm/sec (vertical duct) and 3,000 cu cm/sec (horizontal duct) was added as follows: One-fourth was premixed with methane and added to the disperser; the remainder was added in separate streams as shown in figure 2. The disperser needle and exit tubes to the flame ducts were vibrated continuously to avoid clogging.

[6]Ultrafine grade supplied by Bituminous Coal Research Company, Pittsburgh, Pa. Percent volatiles, 37; percent ash, 4.8.

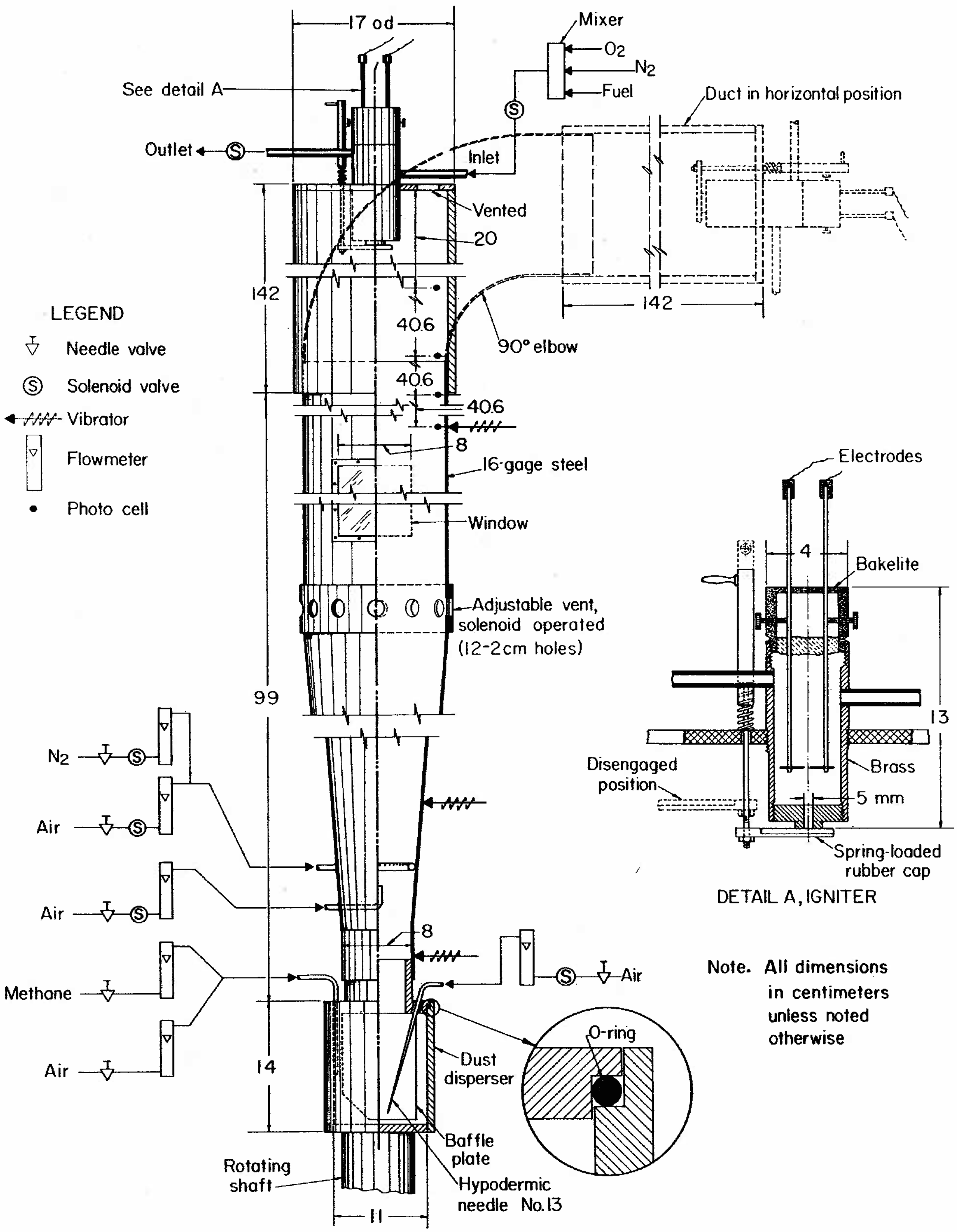


FIGURE 2. - Flame Duct for Vertical and Horizontal Flame Propagation.

Average dust concentrations in the flame ducts were determined for a given time interval by filtering the entire flowing suspension through a glass-wool cartridge and measuring the weight gain. Dust concentrations measured in this way at the outlet of the flame duct and of shorter ducts of the same diameter were uniform to within 5 percent. Local coal dust concentrations at different positions in the flame ducts were determined by filtering the flow through a paper extraction thimble held in a 1.0-cm-diameter isokinetic sampling probe. Local dust concentrations at various longitudinal and radial coordinates in the vertical flame duct were uniform to within ±20 percent. Coal dust concentrations in the last 100 cm of the horizontal duct were determined at three vertical planes 30 cm apart. Vertical dust gradients at each plane in the horizontal duct were approximately constant at $\frac{3 \text{ mg/liter}}{\text{cm}}$ (increasing from top to bottom of duct). The longitudinal dust gradient was $\frac{0.25 \text{ mg/liter}}{\text{cm}}$ in the last 100 cm of horizontal duct (decreasing with increasing distance in the direction of flow). Methane concentrations were uniform throughout both flame ducts and reproducible to within 0.5 percent.

EXPERIMENTAL PROCEDURE

The hybrid mixtures flowing through the flame ducts were ignited in most cases by a pulsed turbulent hot gas jet at the axis near the downstream open end. The hot gas ignition jets were produced by explosion of a methane-oxygen mixture in a 76 cu cm chamber, and passage of the hot combustion products through a cylindrical channel 0.5 cm in diameter and 1.0 cm long. The channel was capped during filling to prevent leakage into the flame duct prior to firing. Peak temperature and length of the hot gas jet were determined in a previous study (4) to be 2,750° K and 12 cm, respectively. In some experiments the ignition source was a capacitance spark (either approximately 0.7 millijoule or 0.2 joule) placed at the same ignition position as the hot gas jet. Electrode spacing was 2 mm. The criterion for establishing lower limit concentrations of flame propagation was two out of three times for flame travel through the complete duct length. In most experiments flame propagation was in mixtures at about 1 atmosphere pressure. Higher pressures were avoided by means of adjustable vent holes at the far end of the flame duct that were automatically opened at the instant of ignition.

Flame speeds in the ducts were measured from Visicorder[7] records of the amplified signal of the photoelectric cell detectors. Speeds and shape of flames ignited by hot gas jets were also measured by black-and-white and color Fastax movies (4,000 frames/sec). Initial speeds and configuration of flames ignited by electric spark were determined from streak camera photographs.

[7]Reference to trade names is for information only and endorsement by the Bureau of Mines is not implied.

EXPERIMENTAL RESULTS

Flame Speeds

Steady-state flame propagation was not achieved in flame travel through the 1.8-m ducts. Flame speeds ranged from 55 to 243 cm/sec for the downward flame and 47 to 201 cm/sec for the horizontal flame (table 1). The flame speed generally decreased as the flames propagated through the horizontal duct, perhaps because coal dust settled out progressively; flame speeds in the vertical duct appeared to pass through a minimum value midway in the duct. Maximum flame speeds were higher in the vertical than in the horizontal duct.

TABLE 1. - Downward and horizontal flame speeds of lower limit mixtures of coal dust-methane-air

Coal dust, mg/liter	Methane, mg/liter	Total fuel concentration, F[1]	Flame speed,[2] cm/sec		
			Station 2[3]	Station 3[3]	Station 4[3]
DOWNWARD FLAMES					
0	35	0.58	(4)	(4)	(4)
17	29	.57	166	109	153
24	27	.59	243	55	148
35	19.5	.60	133	123	134
47	10.5	.57	57	77	104
53	7.2	.53	90	90	94
HORIZONTAL FLAMES					
0	37	0.56	155	139	87
27	25.5	.61	201	112	101
38	16	.57	173	100	85
51	12.5	.64	125	109	62
69	4	.63	79	53	47

[1]Fraction of stoichiometric.
[2]Based on harmonic averages of several runs. All velocities were corrected for velocity of unburned mixture.
[3]Stations spaced 40.6 cm apart.
[4]Not measured.

In the lower limit mixtures, average flame speeds decreased as the coal dust concentration increased and methane concentrations decreased. Equations 1 and 3 relate the concentrations of methane with concentrations of coal dust at the lower flame propagation limits. Equations 2 and 4 relate flame speeds between the third and fourth flame-detector stations with concentrations of coal dust in the presence of associated concentrations of methane at the lower flame propagation limits.

For downward propagation (mixtures containing 0 to 53 mg/liter coal dust):

$$m = 35.1 - 0.24\,c - 0.0056c^2, \quad (1)$$

$$V = 191 - 1.78c^2. \quad (2)$$

For horizontal propagation (mixtures containing 0 to 69 mg/liter coal dust):

$$m = 37.0 - 0.49c, \tag{3}$$

$$V = 105 - 0.0118c^2, \tag{4}$$

where c and m are concentrations of coal and methane in mg/liter and V is the flame speed in cm/sec. The probable percent error of equations 1 through 4 are 2.76, 10.6, 6.34, and 18.1, respectively.

Flame speeds were also measured from Fastax movies of flames propagating through horizontal transparent plexiglass tubes of the same diameter and length as the metal flame ducts. Within the first 30 cm of flame travel, movie records indicated apparent flame speeds in the range of 10,000 to 13,000 cm/sec, owing to progressive ignition in the horizontal direction. These speeds are approximately 100 times the average flame speeds through the entire length of duct. Corresponding flame speeds in the radial direction were approximately 1,500 cm/sec.

Flame speeds of downward propagating flames ignited by a capacitance spark were also measured by means of the photocell detector system. Flames of near limit hybrid mixtures ignited by an "overdriving" hot gas jet were faster than those ignited by a spark; higher fuel concentrations were required for equal flame travel with spark ignition (table 2).

TABLE 2. - Flame speeds of lower limit hybrid mixtures ignited by electric sparks and hot-gas jets (flame duct open at both ends; flame propagation downward)

Coal dust, mg/liter	Methane, mg/liter	Flame speed, cm/sec		
		Station 2[1]	Station 3[1]	Station 4[1]
SPARK IGNITION				
35	37	21	23	([2])
35	38.5	25	30	([2])
35	40	45	52	49
HOT GAS IGNITION				
35	19.5	133	123	134
35	17.5	100	82	([2])

[1]Stations spaced 40.6 cm apart.
[2]Flame did not reach station.

Total Fuel Concentrations and Equivalences for Flame Propagation in Lower Limit Hybrid Mixtures

Total fuel concentrations for flame propagation through the entire duct were about the same for the vertical and horizontal duct positions (table 1). These concentrations, expressed as fraction of stoichiometric,[8] ranged from 0.56 to 0.64 in the horizontal duct and from 0.53 to 0.60 in the vertical duct.

[8]Fraction of stoichiometric is the ratio of total fuel concentration to concentration required for complete combustion.

Data in table 3 present individual concentrations of coal dust and methane and the corresponding equivalences which were computed from equations 1 and 3. The flame propagation equivalences in table 3 are based on mixtures which could propagate flame for about 120 to 130 cm beyond the ignition zone. These flames are not overdriven for most of their history. Their equivalences are lower than the quenching equivalences reported in reference 3 but higher than the "overdriven" ignition equivalences obtained with the same ignition source, which are reported in reference 4. Equivalences are constant for horizontal propagation; they vary inversely with coal dust concentration for downward propagation, as was reported in reference 3.

TABLE 3. - Experimental concentrations of coal dust-methane-air mixtures and computed equivalences for lower limits of flame propagation, hot-gas ignition, and flame quenching

Coal dust, mg/liter	Methane, mg/liter				Equivalences			
	Flame propagation		Hot gas ignition[1]	Quenching[2]	Flame propagation		Hot gas ignition[1]	Quenching[2]
	Horizontal	Vertical			Horizontal[3]	Vertical[4]		
5	35	35	17	38	2.0	3.3	-	-
15	30	29.5	7.5	36.5	2.0	2.4	0.98	3.8
25	25	24	3.0	33	2.0	1.9	1.11	2.9
35	20	19.5	-	30.5	2.0	1.6	-	2.6
45	15	12.5	-	27	2.0	1.4	-	-

[1]Ignition source is hot-gas jet produced by explosion of a stoichiometric mixture of methane and oxygen (4).
[2]At constant quenching distance of 3 cm (3).
[3]From equation 3.
[4]From equation 1.

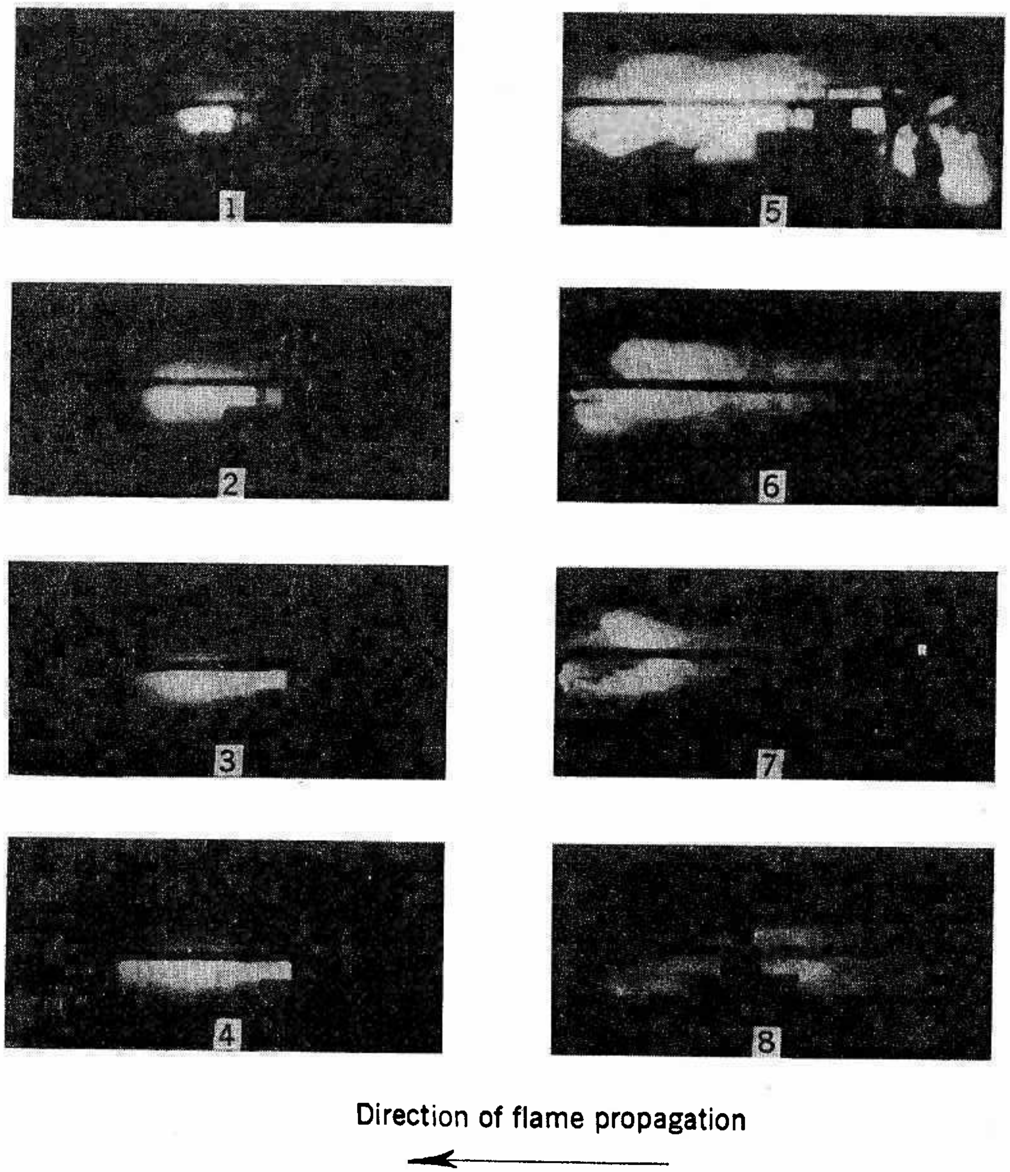
Flame Propagation Following Ignition by "Overdriven" Hot-Gas Jet and Electric Spark

As previously noted, Fastax movies of horizontal flames of lower limit mixtures (fig. 3) indicate different flame speeds for the initial and later stages of flame propagation. The flame advances in the axial direction for approximately 30 cm at about the same rate (10,000 - 13,000 cm/sec) as the hot-gas jet. At the same time it spreads radially at about 1,500 cm/sec. The luminosity and flame speed are much higher near the ignition source than during the later stages of flame movement. There is a high degree of turbulence in the hot burned products behind the propagating flame. As the flame progresses through the horizontal tube, the leading flame front moves faster in the trough portion than in the upper part, possibly owing to the vertical dust gradients.

Flames in the 15.2-cm duct were also ignited by 0.2-joule capacitance sparks and were observed with a streak camera (fig. 4). Initial flame movement was much slower and smoother than with hot gas ignition. As the spherical flame grew (at less than 100 cm/sec) many dust particles were ignited at the flame front. These particles and those ignited later did not travel with the expanding flame front but remained behind and continued to burn without apparent movement for approximately 1 to 3 milliseconds.

Flame Propagation Above Lower Concentration Limit

Flame speeds above the lower concentration limit were determined in the vertical duct for a few mixtures (table 4). For these runs, the adjustable vents at the bottom end of the vertical flame ducts were either kept closed or were opened at the instant of ignition. (Partial duct closure did not have any appreciable effect.) Observed flame speeds were in the same range as flames of lower limit concentrations. Although these runs are too few to draw conclusions, they suggest that the flame speed is not a strong function of hybrid fuel-air composition, when the fuel is predominantly coal dust and the mixture is fuel-lean.



LEGEND

Position	Time after preceding photograph, sec	Distance from ignition port to end of flame, cm
1		19.9
2	0.0004	28.5
3	.0004	32.3
4	.0014	37
5	.0126	43.7
6	.0347	47.5
7	.0287	49.4
8	.392	80.7

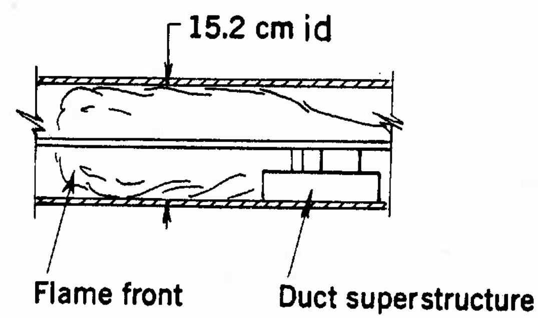
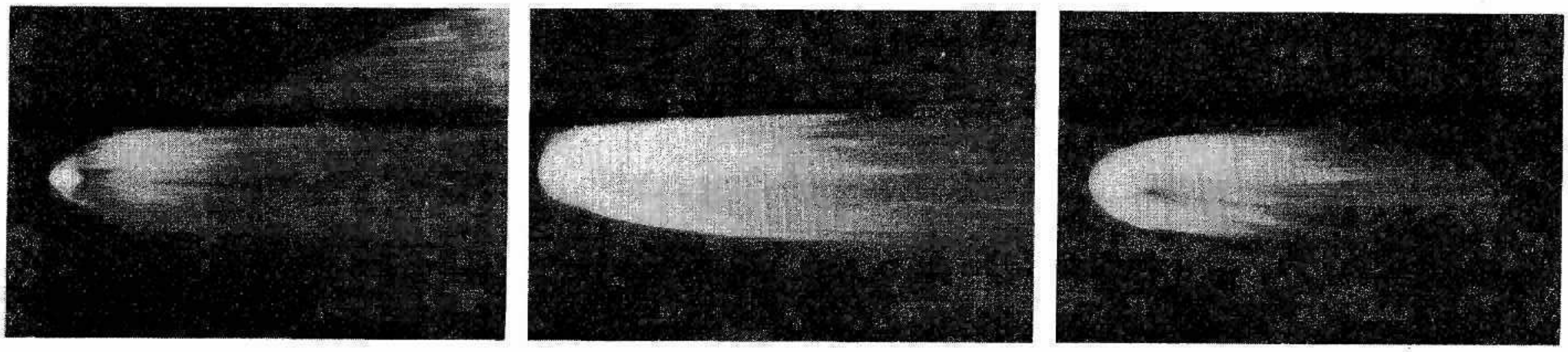


FIGURE 3. - Fastax Motion Pictures of a Coal Dust-Methane-Air Flame Propagating Through a Horizontal Duct (15.2 cm id x 1.8 m). Coal dust concentration, 51 mg/liter; methane, 13 mg/liter.



A B C

FIGURE 4. - Streak Photographs of Ignition of Coal Dust-Methane-Air Mixtures by Electric Sparks. Coal dust concentration 35 mg/liter. *(A)* methane concentration, 5.2 percent, *(B)* methane concentration, 4.8 percent, *(C)* methane concentration, 4.4 percent. Scale: normal size. (partial ignition in *(C)*).

TABLE 4. - Downward flame speeds of coal dust-methane-air mixtures in the vertical flame duct (total concentrations above lower limit)

Coal dust, mg/liter	Methane, mg/liter	Total fuel concentration, F[1]	Flame speed, cm/sec		
			Station 2[2]	Station 3[2]	Station 4[2]
DUCT OPEN ONLY AT IGNITION END					
35	34.0	0.81	135	141	148
35	33.0	.79	98	80	119
35	31.0	.76	159	73	100
35	28.5	.72	119	77	82
35	[3]24.5	.68	113	68	110
35	22.5	.63	107	([4])	([4])
DUCT OPEN AT BOTH ENDS					
35	34.0	0.81	115	56	60
35	33.0	.79	109	108	103
35	29.5	.73	159	114	172
35	21	.68	124	123	122

[1]Fraction of stoichiometric.
[2]Stations spaced 40.6 cm apart.
[3]Limit.
[4]Flame did not reach station.

DISCUSSION

The data of table 3 show that the fuel concentrations required at lower limits of flame propagation and the equivalences are higher for continuing flame propagation than for short-lived flame propagation in the vicinity of an "overdriven" ignition. The tabulated total fuel concentrations of table 1 are approximately the same as the fuel concentration at the lower limit of flammability of many hydrocarbon-air mixtures (fraction of stoichiometric = 0.55).

Data in tables 2 and 3 indicate that the minimum fuel concentrations, flame speeds, and flame propagation distances depend on the energy of the ignition source. Previous work (4) also showed that lower limit fuel concentrations for ignition and equivalences of hybrid mixtures were inversely related to the energy of the hot-gas-jet ignition source. In reference 4, the trend to lower concentrations and equivalences with increasing hot-gas-jet energies and temperatures was attributed to faster and greater consumption of coal dust in the primary combustion zone owing to greater conductive, radiative, and convective transport from the "overdriving" ignition source. Abnormally rapid flame movement following "overdriven" ignition of hybrid fuels is attributed to these same factors. Increased transport of heat from such ignitions and its persistence to distances far downstream of the ignition source is probably critical for maintaining marginal dust flames and may explain increased difficulty in the extinguishment of normally fast-burning flames. Thus it would appear that "overdriven" ignitions in coal mines are particularly hazardous, since fast flames are more difficult to quench than slow flames (3).

CONCLUSIONS

1. Equivalences of coal dust to methane based on lower limit flame propagation are constant for horizontal propagation; equivalences vary inversely with coal dust concentration for downward propagation.

2. Fuel concentrations at lower limits are lowered and corresponding flame speeds are increased by high-energy ignition sources.

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