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EXPERIMENTAL RESEARCH ON FLAME SPECTRA OF METHANE-COAL DUST EXPLOSIONS

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ABSTRACT: The significance of experimental research on flame spectra of methane-coal dust explosions is explained. Weak explosions of methane-coal dust-air mixtures were carried out in a large-scale tube of Ø 200cm × 2900cm with one end open, and the absolute radiation intensities as well as their variation under different conditions for characteristic wavelengths of 0.8875, 1.000, 1.505, 2.801, and 4.346μm were obtained by using small angle of view and a multichannel detector developed by us. The experimental results are discussed and compared with those published abroad. Based on the absolute radiation intensity measured at wavelength 4.346μm and the selected blackbody radiation model, the temperature of explosion flame was determined. The results obtained are not only of great practical importance to the industry but may also be used in the study of flame and chemical kinetics.

KEY WORDS: methane-coal dust, explosion isolation, multichannel spectral detector, characteristic spectra, spectral radiation intensity, flame temperature.

I. INTRODUCTION

The explosion of methane-coal in air is one of the serious natural disasters occurring in coal mines. Prevention of such disasters is taken seriously by the governments as well as engineers and scientists. A vast amount of work is done on techniques and measures of prevention and isolation of explosions under different specific conditions. It was proved that if explosion intensity of methane-coal dust is very weak, passive device of explosion isolation is no longer effective and the propagation of explosion flame could not be prevented. In view of this situation, the development of automatic device for explosion prevention and isolation was started abroad in the seventies. This kind of device is not handicapped by the weak explosion conditions. The automatic system is usually made up of three parts: the detector, the microcomputer control system and the explosion cut-off device. The accuracy and reliability of the detector are most important. Different kinds of detectors have been used abroad. Among them all the infrared detectors adopted the wavelengths shorter than 2μm in the near infrared, and is easily disturbed by spectral radiation of miner's lamp and others in the coal mine. Ultraviolet detector is likely to be influenced by electric sparks and others. As for pressure transducer, it is also easily interfered by all kinds of pressure waves. In general, all sensors mentioned above can easily cause mis-diagnosis. In view of the above situation, we take characteristic spectra of explosion flame, which are different from those of the other light sources in coal mine, as the basis for making optical triggering detector. By this way, trigger signals with both rapid response and reliability were defined. The detector avoids mis-diagnosis and is already used in our newly developed automatic device system for explosion isolation.

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The spectral characteristic study of explosion flame for methane-coal dust is one of the important topics in dust explosion. Yet at present, this experimental research is carried out only in a few countries of the world.

By use of the multi-channel detector developed in our Lab., in a large-scale simulating explosion test tube of ∅ 200cm × 2900cm with one end open, the experimental research of spectral characteristic of explosion flame for methane-coal dust under different conditions was carried out. Peak-pressure and wave velocity of explosion were measured. Absolute intensity of spectral radiation was obtained at different wavelengths and the experimental results were discussed and compared with those from abroad. According to the physical model of blackbody radiation and the absolute radiation intensity measured at $\lambda = 4.346\mu m$, temperature of the explosion flame was obtained. The results are of considerable value in preventing the explosion calamity of methane-coal dust; especially in developing the optical trigger detector of automatic system for explosion isolation under ground and in the diagnosis of high temperature flames. It is also useful in combustion and chemical kinetics studies.

II. EXPERIMENTAL DEVICE AND MEASURING SYSTEM

1. Experimental device

By use of a tube as shown in Fig.1, the explosion of methane-coal dust in coal mines was simulated at different conditions.

(1) Simulating tube. The gas mixture chamber of $18m^3$ is sealed by a diaphragm at closed-end of the tube in Fig.1. The chamber is filled with mixed gas of different methane-air proportions. After stirring, explosion in the premixed gas was initiated immediately by a special igniter. After

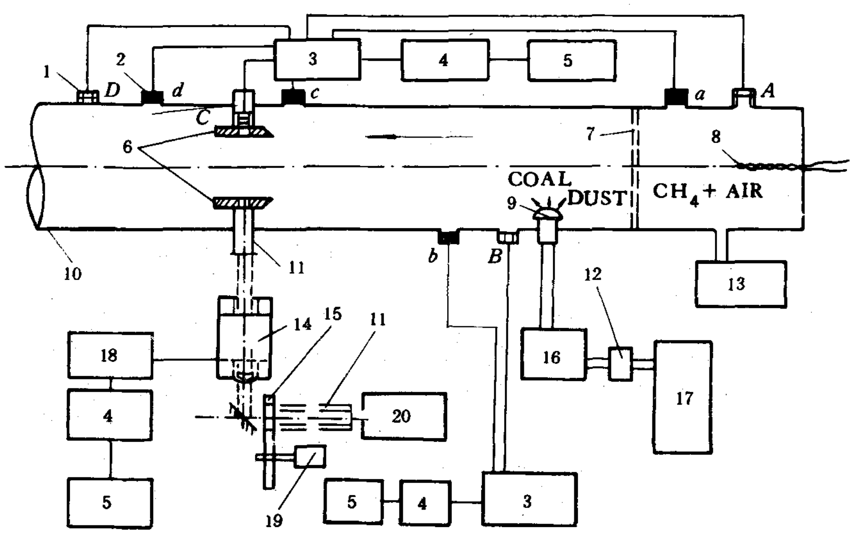

Fig.1 Measurement device of spectral radiation of explosion flame in CH_4-coal dust-Air

1. pressure transducer	2. Flame transducer	3. telemeter	4. signals storage
5. signals analyzer.	6. diversion plate	7. Sealed diaphragm	8. ignitron
9. dusting device	10. Explosion tube	11. light duct	12. electromagnetic valve
13. CH_4 determination divice	14. spectral detector	15. light modulator	16. coal dust vessel
17. pressure stroge tank	18. amplifier	19. motor	20. blackbody Furnace

explosion, the fronts of both explosion pressure wave and flame propagate at high speed along the tube. When explosion experiments of mixtures of CH_4-Air-Coal dust were made, a dusting device shown in Fig.1 was used. First, CH_4 was mixed with air, then an electromagnetic valve was opened, and coal dust was injected into the tube by compressed air. Immediately, after the coal dust cloud was formed it was ignitor by a special igniter. Time sequence of the whole system was completed automatically by a suitable synchronizing device.

(2) Measurement system for pressure and flame velocity. Flame and pressure transducers developed by us were installed at different positions of the tube. Flame velocity, peak pressure and pressure wave front velocity were measured by the use of synchronizing trigger, telemetering and data acquisition system.

(3) Flow diversion plate. In the simulation tube, in order to obtain more homogeneous high temperature flame gas and to avoid the influence of cold boundary layer at the tube wall, flow diversion plates with definite entering angles were used (Fig.1), with which accurate spectral measurement of high temperature flame between plates can be accomplished.

2. Spectral measurement system

(1) Multi-channel instrument. According to the requirement of spectral measurement, based on the characteristic spectra of methane-coal dust explosion products and the continuous radiation analysis we developed a multi-channel instrument, which consists of lens, interference filter with the central wavelengths of 4.346, 2.801, 1.505, 1.000 and 0.8875μm, a suitable infrared detector, an amplifier, etc. The absolute radiation intensity of explosion flame spectra for methane-coal dust was measured by this instrument.

(2) Calibrating system of absolute radiation intensity. The multi-channel instrument was calibrated with a high temperature blackbody furnace of 1073—2773K through a 50 mm aperture on the furnace. Besides, an in-situ calibration system consisting of CTG–1 model blackbody furnace, light duct, light modulator and mirror was also fixed on the tube. Sensitivity of the multi-channel instrument was calibrated with the same optical path as that of the measurement system.

(3) Recording system. High speed DM–7100 and SM–2100 multi-channel acquisition systems were used for acquisition, storage and analysis of the measured signals.

III. PRINCIPLE AND METHOD OF SPECTRAL MEASUREMENT

Chemical reaction of methane-coal dust-air explosion flame is very complex. Its reactive products consist of molecules, such as CO_2, H_2O etc., and also atoms as well as free radicals. Molecular vibrational and rotational energy are easily excited at about 2273K and thus different molecular spectra are emitted. These are the main part of spectral radiation of the deflagration system. The characteristic spectra are mainly at near-infrared and medium infrared region. For example, emission bands of CO_2 are at about 2.7 and 4.3μm, and that of H_2O at about 1.38, 1.87 and 2.70μm. Although there are radiations in ultraviolet and visible light region from free radical OH, etc. their intensities are small because of the lower temperature. Owing to the increase of carbon atoms and particles there is marked continuum radiation in explosions with coal dust.

1. Measurements of spectral radiation intensity

By the comparison of radiation energy between explosion flame and blackbody furnace under the same light path, we obtained the following formula[1] for $I_{a\lambda}$, the absolute intensity of flame spectral radiation,

$$I_{g\lambda} = \frac{R_{g\lambda}}{R_{b\lambda}} \cdot \left(\frac{\tau_b}{\tau_g}\right) \cdot I_{b\lambda} \tag{1}$$

where $$I_{b\lambda}(T_0) = \frac{C_1}{\lambda^5(e^{c_2/\lambda T_0}-1)}\left(\frac{\mathrm{W}}{\mathrm{cm}^2 \cdot \mathrm{ster} \cdot \mu\mathrm{m}}\right) \tag{2}$$

$I_{b\lambda}$ is radiation intensity of blackbody; λ is wavelength; T_0 is actual temperature of blackbody; the first radiation coefficient $C_1 = 1.191062 \times 10^4 \mathrm{W} \cdot \mu\mathrm{m}^4 / \mathrm{cm}^2 \cdot \mathrm{ster}$; the second radiation coefficient $C_2 = 1.438786 \times 10^4 \mu m \cdot K$; $R_{g\lambda}$ and $R_{b\lambda}$ are photoelectric readings of explosion flame and radiation of blackbody furnace respectively with the same detector of the same unit, and obtained from experiment and calibration separately; τ_b and τ_g are transmissivity of quartz window of blackbody furnace and sapphire window of test tube respectively, both measured beforehand. Thus based on $R_{b\lambda}$ and $I_{b\lambda}$ from calibration, $R_{g\lambda}$ of explosion flame at wavelength λ from experiment and with known τ_b and τ_g we may find absolute spectral intensity of explosion flame $I_{g\lambda}$ through Eq.(1).

2. Absolute calibration

State temperature may be up to about 2300K for explosion of methane-coal dust. Since the temperatures of the blackbody furnace CIG–1 on site were rather low and could not match with that of the high temperature flame, static calibration with another high temperature blackbody furnace WIL–11 was necessary. Through calibration and necessary data processing, the relations between calibrating signal V_λ and the related radiation intensity $I_{b\lambda}$ of detectors at different wavelength channel were obtained. For example, for detector at wavelength 4.346μm, the regression relation $V_\lambda(\mathrm{mV}) \sim I_{b\lambda}$ (W/cm^2 · ster · μm) and relevant coefficients r are shown in Fig.2.

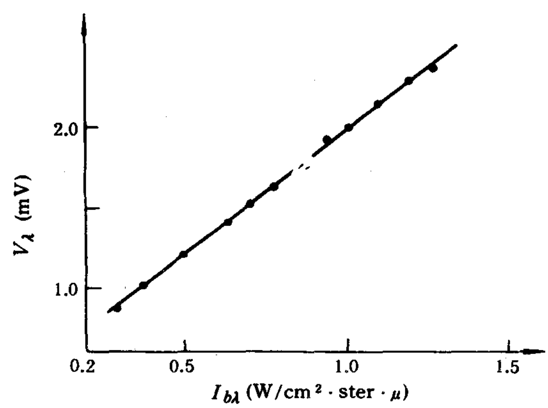

Fig.2 Relation of calibration signal (V_λ) and radiation intensity ($I_{b\lambda}$) for $\lambda = 4.346\mu$m (TecdHg)

• Calibration value

$V_\lambda = (0.4437 + 1.5445\ I_{b\lambda})(\mathrm{mV})$

$r = 0.998$

IV. TEMPERATURE DETERMINATION OF EXPLOSION FLAME

Main products of methane-coal dust explosion are molecules of CO_2, H_2O, etc. Therefore their band spectra radiations are most important, although continuum radiation of carbon particles also exists. According to Tourin's experimental results[2] on spectral emissivity of CO_2 under different states at about $\lambda = 4.30\mu$m, it shows that at $T = 1273$K and $P = 9.331 \times 10^4$Pa, $PL = 1.184 \times 10^4$m·Pa, and the emissivity $\varepsilon_\lambda = 1$ within the range of wavelengths 4.18 to 4.55μm. It implies that when light path $L=0.127$m, high temperature gases are already optically thick. In [3] the explosion experiments with 9.1% CH_4 in air were made in a 9-liter cylindrical vessel. When $T=2000$K and $PL=2.533\times10^4$m·Pa, the experiments showed that in the vicinity of wavelength 4.4μm $\varepsilon_\lambda=1$, i.e. blackbody radiation.

From our own experiments with specific methane-coal dust, the results are: $L=1.00$m, $P=(1.216\times10^5-1.520\times10^5)$Pa, temperatures being about 2000K, and $PL=(1.216\times10^5-1.520\times10^5)$m·Pa. Therefore, it can be sure that $\varepsilon_\lambda=1$ in the vicinity of wavelength 4.346μm, and in our case there seems to be no problem to investigate the radiation of methane-coal dust explosion based on the blackbody model. Based on the above analysis, the explosion flame temperature might be determinated by the band radiation intensity of CO_2 at wavelength 4.346μm. The relevant radiation intensity $I_{b\lambda}$ is given in Fig.2. Then explosion flame temperatures can be found through equation (2).

V. EXPERIMENTAL RESULTS AND ANALYSIS

1. The results of pressure wave velocity, peak pressure and flame velocity for different stoichiometric conditions of CH_4-air and CH_4-coal dust in air are shown in Table 1. In standard coal-sample used the moisture, ash content, volatiles of analytical base and volatiles of combustible base are 2.6%, 16.2%, 39.0% and 48.1% respectively. The size of 0.7mm$>D>$0.15mm and $D<$0.075mm are 1.9% and 78.6% respectively.

The results from Table 1 indicate

(1) Flame transducers are fixed at position c and d of tube wall in Fig.I, 19m and 23m from the end of detonation chamber respectively. Flame velocity between c and d increases linearly with CH_4 content. At the same CH_4 content, flame velocity increases noticeably when coal powder added is near 200g/m^3; but the influence of coal powder on flame velocity is small for lower powder content.

(2) Pressure transducers are fixed at positions A and B in Fig.1, 3m and 27m from the end of detonation chamber respectively. Pressure wave velocities between A and B are all higher than the sound velocity. The pressure at position C which is at the same cross-section with spectral measurement window ranges from 1.216×10^5Pa to 1.520×10^5Pa, which indicates weak explosion.

2. As shown in Fig.3, in CH_4-air explosion, the relation between CH_4 content and radiation intensity of wavelength 4.346μm is linear. This is due to linear growth of CO_2 molecules in the vibrational excitation state.

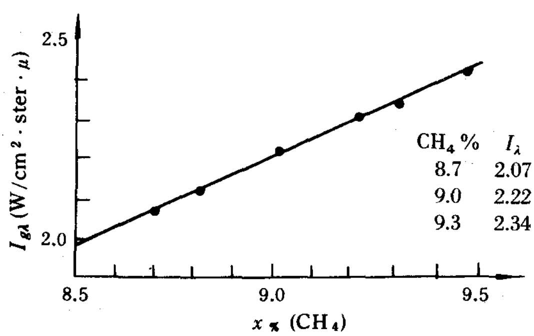

Fig.3 Relation of CH_4 content and $I_{g\lambda}$ for $\lambda=4.346\mu$m

$$\begin{cases} I_{g\lambda}=(-1.84+45.0\ x\ \%)(\mathrm{W/cm^2\cdot ster\cdot\mu}) \\ r=0.998 \end{cases}$$

• experimental points $\times$ %(CH_4)

Table 1

Typical flame velocity, explosion wave velocity and peak pressure

No.	Detonation conditions		Flame velocity (m/s)				Explosion wave velocity (v)m/s, and peak-value pressure P(Pa)				
	CH_4%	coal dust (g/m^3)	ab**	bc**	cd**	CD(v)	C*(P)	D*(P)	AD(v)	A*(P)	D(P)
1	8.0	0			45.5		1.270×10^5				
2	8.1	208	67.8	231	90.9				(394)	1.446×10^5	1.331×10^5
3	8.0	194	64.5	167	90.9				590	1.419×10^5	1.270×10^5
4	8.5	0	56.3	71.4	74.1				406	1.298×10^5	1.182×10^5
5	8.5	68.8	45.5	54.5	90.9	(417)	1.270×10^5	1.149×10^5	407		1.149×10^5
6	8.5	80.3	52.6	57.7	87.0		1.432×10^5				
7	9.0	0	56.3	61.2	90.9		1.230×10^5				
8	9.0	0	74.1	69.8	90.9						
9	9.3	0	42.6	36.8	108				838	1.332×10^5	1.241×10^5
10	9.3	0	42.6	50.0	111				634	$>1.350 \times 10^5$	1.365×10^5
11	9.3	0	56.3	125	105				703	1.338×10^5	1.202×10^5

* 1. Pressure transducers are fixed at A, C and D position in Fig.1. They are 3m, 17m and 27m apart from end wall of detonation chamber respectively.

** 2. Flame transducers are fixed at a, b, c and d position in Fig.1. They are 5m, 13m, 19m and 23m apart from end wall of detonation chamber.

3. Spectral measurement window is at the same cross-section with position C for pressure.

3. Spectral radiation intensity and temperature of a typical explosion flame are shown in Tables 2, 3 and Fig.4 under conditions of CH_4-coal dust in air. The experimental results indicate: (1) coal dust with concentration lower than $100 g/m^3$ has small influence on spectral radiation intensity; but with coal dust concentrations close to $200 g/m^3$, the influence increases noticeably; (2) when fire-extinguishing chemical exists at experimental section, radiation intensity at wavelength $4.346 \mu m$ drops evidently under condition of CH_4-air as shown in Table 2 and Fig.4; (3) The temperature increases with the increase of CH_4 content (see Table 2).

Experiments abroad in the eighties were carried out in small sealed vessels and are different from our conditions. The results of our radiation intensity tests at wavelength $4.346 \mu m$ agree well

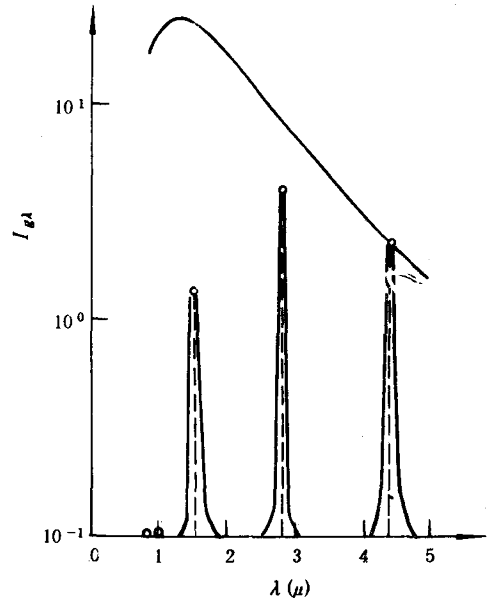

Fig.4 Absolute intensity of spectral radiation of explosion flame

CH_4(9.3%)

— T_0 = 2278 K planck curve ○ present paper

× with fire extinguishing chemical

Table. 2

Typical radiation intensity and temperature of explosion flame at different conditions

No.	Detonation conditions		explosion flame	$\lambda=4.346\mu m$		$\lambda=2.801\mu m$		$\lambda=1.505\mu m$	
	CH_4%	coal dust (g/m³)	temperature (K)	$I_{b\lambda}$	$I_{g\lambda}$	$I_{b\lambda}$	$I_{g\lambda}$	$I_{b\lambda}$	$I_{g\lambda}$
1	8.0	34.4	1905	1.639	1.639	5.00	5.00	10.27	0.40
2	8.5	68.8	2163	2.122	2.122	7.09	4.60	18.79	1.70
3	8.7	0	2135	2.070	2.070				
4	9.0	0	2200	2.231	2.231	7.58	4.80	21.08	0.37
5	9.3	0	2278	2.344	2.344	8.10	4.20	23.56	1.35
6*	9.3	0	1580		1.070				

* With fire-extinguishing chemical.

with that of Cashdollars[3] et al., but our results at wavelength 2.801 and 1.505 μm are higher than theirs. These may come from the differences in the devices, the measurement conditions, the

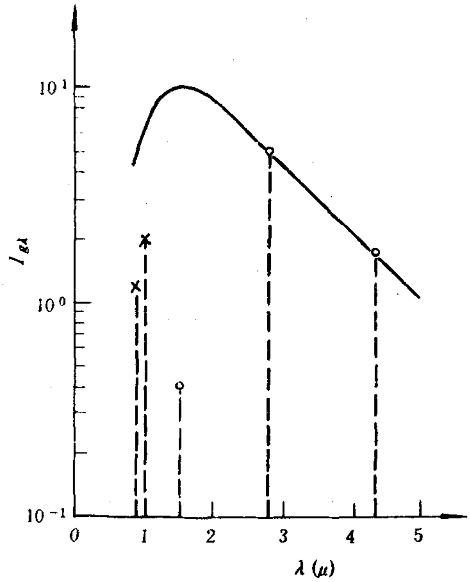

Fig.5 Absolute intensity of spectral radiation of explosion flame
—— T_0 = 1905 K planck curve
○ CH_4(8.0%), coal dust (34.4 g/m³)
× CH_4(8.0%). coal dust (194g/m³)

Table.3

Radiation intensity of explosion flame at different conditions

No.	Detonation conditions CH_4 %	Coal dust (g/m³)	λ=0.8875μm $I_{g\lambda}$(w/cm²·ster·μ)	λ=1.00μm $I_{g\lambda}$(w/cm²·ster·μ)
1	8.5	0	~0	~0
2	9.0	0	~0	~0
3	9.3	0	~0	~0
4	8.0	194	1.20	1.95

bandwidth and so on. The relative error of the spectral radiation intensity measurements is about 30%. Based on radiation theory the following formula was deduced:

$$\frac{\delta I_\lambda}{I_\lambda} \propto \frac{C_2}{\lambda T_g} \cdot \frac{\delta T_g}{T_g} \tag{3}$$

where T_g is explosion flame temperature. Since the relative error of the radiation intensity, measured at wavelength 4.346μm, is about 10%, the relative error of T_g is about 5%.

VI. CONCLUSIONS

1. In the weak explosion region of spectral measurement, using detectors with small angle of view ($\sim 1.3°$), the absolute spectral radiation intensities are obtained at different states. The influence of CH_4 quantity and coal dust content on the spectral radiation intensity of explosion flame are also investigated. The experimental results are reliable and can be used in the design of automatic device of explosion isolation in coal mines.
2. As for explosion of CH_4-coal dust, owing to strong signal at 4.346μm waveband, the infrared detector gives high sensitivity, rapid response and good stability; and can be used to diagnose temperatures of explosion flame.
3. The multi-channel instrument developed by us can be used not only for measuring the flame spectral intensity and temperature but also for the study of other properties and kinetics in CH_4-coal dust explosions.

Mr. Wang Xiaoyu and Mr. Cai Zhouquan also took part in this research work.

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