Combustion and detonation waves in methane mixtures with suspensions of fine coal particles

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Abstract. Combustion and detonation waves in hybrid systems of gas mixtures CH$_4$/air with suspensions of coal particles 1–200 µm in size in a vertical shock tube (70 mm in diameter and 6.75 m long) are studied experimentally. The structure and parameters of the waves in gas mixtures without coal dust and in the same mixtures containing suspensions of a coal powder with a mean-volume density of 23–534 g m$^{-3}$ are compared. XRD patterns of the coal powder are analyzed.

1. Introduction

Because of fires and explosions in coal mines, an important aspect to study includes the combustion waves and transonic explosive modes in methane-air mixtures, as well as methods for suppressing these processes [1-5]. The walls of the coal mine channel (mainly the lower walls) are covered with coal dust, which is also contained in smaller amounts in the channel volume. The concentration of coal dust suspended in air in the mine $\rho \leq 1$ g m$^{-3}$ is lower by 2-3 orders of magnitude than the lower flammability limit $\rho^* \approx 30-80$ g m$^{-3}$. The primary blast wave (shock wave (SW) with combustion products moving at a certain distance from the SW front) in mines is initiated either by blasting explosive charges or by spontaneous ignition of the methane-air mixture. The following situations are also possible: being entrained by the gas flow behind the SW front from the channel walls, coal dust transforms to a suspended state, becomes heated, ignites, and enhances the explosion wave.

Experiments under close-to-real conditions are performed by separating some part of the channel with a length of 3-20 calibers and 1-3 m in diameter by a paper or polyethylene membrane and filling this part of the channel by methane [3]. After methane mixing with air, the mixture is initiated by an igniter with the energy up to several kJ. A compression wave with transonic parameters is formed in this region in the methane-air mixture. Behind the membrane, the explosion wave propagates through the air medium, and it can be attenuated by adding chemically inert or flame-extinguishing dust. The detonation in the chemically active CH$_4$+2O$_2$+N$_2$ mixture and the flame propagating behind the detonation wave were completely quenched by using a sand dust curtain [6]. The processes of flame acceleration and transition to detonation, combustion, explosion, and detonation in hybrid multiphase systems including an explosive gas and coal dust have been little studied. The goal of the present work was to obtain experimental data on the parameters of combustion and detonation waves in hybrid systems containing a CH$_4$/air mixture and a suspension of fine coal particles.
2. Coal powder

Coal pieces up to 1 cm in size were crushed for 2 hours in a machine containing steel balls 10-40 mm in diameter, and then the fragments were sieved through 200-µm cells. The photographs and elemental composition of coal were obtained by a Merlin compact, Zeiss scanning electron microscope (Figure 1, Tables 1 and 2).

Figure 1. Original fraction of coal (0–200 µm). The left and right spectra were taken on a coal particle and impurity particle, respectively (impurity particles shine).

The main elements of coal are C, O, Si, and Al; the main elements of the impurity are C, O, Si, Al, Fe, Ca, and Mg. The percentage of carbon is lower in the impurity as compared to coal, whereas the percentage values of O, Si, Al, Fe, Ca, and Mg are higher than those in coal dust.

| Element | C    | O    | Mg   | Al   | Si   | S    | K    | Ca   | Fe   | Cu   |
|---------|------|------|------|------|------|------|------|------|------|------|
| Wt.%    | 78.35| 19.75| 0.03 | 0.41 | 0.69 | 0.16 | 0.04 | 0.25 | 0.09 | 0.12 |
| At.%    | 83.44| 15.79| 0.02 | 0.19 | 0.31 | 0.06 | 0.01 | 0.08 | 0.02 | 0.03 |

Table 1. Mean weight and atomic percentage of the main elements in coal particles.

| Element | C    | O    | Mg   | Al   | Si   | P    | K    | Ca   | Ti   | Fe   | Cu   |
|---------|------|------|------|------|------|------|------|------|------|------|------|
| Wt.%    | 25.08| 39.06| 1.95 | 7.79 | 13.33| 0.09 | 0.81 | 2.69 | 0.34 | 8.41 | 0.29 |
| At.%    | 36.98| 43.79| 1.43 | 5.13 | 8.41 | 0.05 | 0.36 | 1.18 | 0.13 | 2.69 | 0.08 |

Table 2. Mean weight and atomic percentage of the main elements in impurity particles.

The coal samples were studied by using a D8-Advance X-ray diffractometer with CuKα radiation. Crystalline impurities in coal correspond to the lines of quartz (SiO₂) and to the lines of kaolinite Al₄[Si₄O₁₀](OH)₈ and chlorite (Mg,Fe,Al)₆(Al,Si)₄O₁₀(OH)₈, which are close to each other. Kaolinite is present in the samples in large amounts (the fractions of Si and Al in the samples are noticeably greater than those of Fe and Mg). There is a wide halo corresponding to amorphous carbon near the angle of 26°, while the crystalline carbon lines are absent.

3. Experimental setup and technique

The experiments were performed in a vertical shock tube with a diameter d=70 mm and test section length of 6.75 m. Before the experiment, the test section was evacuated and then filled by fuel-lean mixtures of gaseous CH₄ and air with addition of a coal dust suspension, which was generated by purging the gas mixture through a container with a coal powder and dust generator. The combustion and detonation waves in the tube were generated by initiating the examined gas mixture with a high-voltage spark or with the use of two lateral initiation sections (IS) separated from the test section by diaphragms and filled by the C₂H₂+2.5O₂ mixture at the initial pressure p₀=0.05–0.30 MPa. The initial temperature was 17-18°C; the mass and volume concentrations of coal dust particles were m=0.6–14 g and ρ=23–534 g m⁻³. The profiles of luminescence and pressure in compression waves were recorded.
by Tektronix TDS2014 oscillographs whose signals were recorded by photomultipliers PMT1–PMT3 and piezoelectric sensors S1–S9 through source repeating multipliers with a time constant of 0.5–2 s. PMT1 was located opposite to sensor S3, PMT2 was placed at a distance of 2.485 m from the test section beginning, and PMT3 was located opposite to S8. The measurement errors were 2% for wave velocity and 5% for pressure.

4. Experimental results

4.1. Gas mixture 0.081CH₄+0.919O₂

The calculated detonation parameters for the mixture are the detonation velocity \( D_0 \approx 1640 \text{ m/s} \) and the cell size \( a \approx 30 \text{ mm} \) [7]. When the gas mixture is initiated by a detonation wave from the IS at \( p_{0i}=0.15 \text{ MPa} \), a detonation wave (DW) is formed in the test section, which reaches a steady-state mode in the second half of the tube. The DW front velocities in regions S1–S9 are \( D_{12}=1232, D_{25}=1186, D_{56}=1190, D_{78}=1682, \) and \( D_{89}=1698 \text{ m/s} \). Based on the measured pressure profiles, the reaction zone length is \( l_r \approx 30-38 \text{ mm} \), and the period of oscillations behind the DW front is \( T \approx 130 \mu \text{s} \) (the frequency is \( f \approx 7.69 \text{ kHz} \)).

The main chemical element of coal is carbon; the temperature of carbon burning is 470°C. The stoichiometric composition of the mixture with addition of carbon is 0.081CH₄+0.919O₂+0.757C. In the test section with a volume of 26.2 liters at \( p_{0i}=0.1 \text{ MPa} \) and complete burning of carbon in this gas mixture, one needs \( m \approx 10.6 \text{ g} \) of coal (\( \rho \approx 405 \text{ g m}^{-3} \)). Under similar test conditions, but with addition of the coal suspension in the test section, the DW reaches an almost steady-state velocity already at the initial part of the shock tube. The pressure at the DW front significantly increases due to deceleration of the gas flow on dust particles. The luminescence intensity behind the DW front increases approximately by 10% and has a rectangular profile over the entire tube length (Figure 2).

![Figure 2. Oscillograms of pressure and luminescence, 0.081CH₄+0.919O₂–coal suspension, \( \rho \approx 191 \text{ g m}^{-3} \); \( p_{0i}=0.15 \text{ MPa}, p_{0}=0.1 \text{ MPa}; D_{12}=1714, D_{25}=1639, D_{56}=1714, D_{78}=1575, \) and \( D_{89}=1575 \text{ m/s} \).](image)

In the case of more intense initiation (\( p_{0i}=0.2 \text{ MPa} \)), the DW propagates in both cases, with an almost steady-state velocity, including the initial part of the tube, but the luminescence in the DW in the presence of the coal dust suspension is more intense and persists for a longer time (>3 ms).

The coal particles start to burn in the reaction zone approximately 30 mm long; fine particles burn down first. The combustion of coal particles extends behind the reaction zone. Coal combustion competes with methane combustion, but the resultant heat release in the reaction zone remains approximately unchanged. After the experiment, there appear structures consisting of almost identical spheres 0.5–100 μm in diameter in the coal powder. A decaying SW propagates over the tube after DW reflection from the end face.
Lower pressures in the test section. To consider the influence of the reaction zone length on the degree of burnout of coal particles and detonation parameters, we performed experiments with reduced initial pressures in the test section. In the experiment without the coal suspension at $p_0=0.025$ MPa (Figure 3), we obtained $l_r=a=120$ mm (it increases inversely proportional to $p_0$). In Figure 3, $b$, the first peaks of luminescence during 0.25-0.75 ms correspond to the methane reaction with oxygen. The second, longer increase in the luminescence in 1.4 ms corresponds to the detonation products of the $C_2H_2+2.5O_2$ mixture from the IS, which gradually lag behind the DW front. The luminescence in the reaction zone lasts for 0.7 ms, corresponding to a distance of about 1 m. In 2.5 m, the DW transforms to a single-head spinning mode with the rotation frequency $f=7.407$ kHz. The velocity of sound behind the DW front can be estimated by using the well-known expression $c=\pi df/1.84$ as $c=885$ m s$^{-1}$.

In the hybrid system consisting of the gas mixture and coal dust suspension, the luminescence in the reaction zone and behind it becomes more intense owing to combustion of coal particles ($f=7.94$ kHz). Therefore, $c=948.5$ m s$^{-1}$, and the temperature behind the reaction zone is 15% higher as compared to the case of detonation in the same gas mixture. The luminescence peaks merge together, the luminescence duration increases (Figure 4, $b$, $c$), and the DW velocity increases approximately by 40 m s$^{-1}$. The DW reflected from the end face of the tube transforms to a decaying SW.

4.2. $CH_4+10.52$ air mixture, no diaphragms in the IS, spark initiation

The calculated parameters for the mixture are $D_0=1770$ m s$^{-1}$, $a=259$ mm, and pressure in the Chapman-Jouget (CJ) plane $P_{CJ}=1.66$ MPa [7]. The mixture is approximately 10% leaner in terms of
methane than the stoichiometric mixture CH₄+9.524 air. In the shock tube with d=70 mm, a steady-state DW does not propagate even in the spin regime because πd<a.

At p₀=0.05 MPa, the mixture cannot be initiated by a spark. Beginning from p₀=0.085 MPa, the mixture can be initiated by a spark, the flame propagates in the close-to-limiting regime, and the DW velocity is D<1 m/s. At p₀=0.1 MPa, the flame propagates over the test section, and the compression waves move faster than the flame front. The flame velocities are D₂₅=325, D₅₆=120, D₇₈=0.91-1.25, and D₈₉=1.44 m s⁻¹. The luminescence in the combustion wave is rather weak and lasts for 70-200 ms.

In the hybrid system, the luminescence intensity increases by more than an order of magnitude, and compression waves become steeper at the end of the shock tube. At ρ=359 g m⁻³ and p₀=0.1 MPa, D₂₅=13, D₅₆=10-15, D₇₈=1.82, and D₈₉=1.15 m s⁻¹.

**Initiation by the C₂H₂+2.5O₂ mixture with the use of the IS.** P₀₀=0.1 MPa, p₀=0.1 MPa, in this case, a decaying blast wave propagates along the test section (D₁₂=1043, D₂₅=886, D₅₆=857, D₇₈=769, and D₈₉=767 m s⁻¹). The flame front velocity between PMT1 and PMT2 is D=600 m s⁻¹; the luminescence lags behind the SW front by 450 µs in this region and already by 4 ms at the PMT3 location. The reflected wave is the wave of steady low-velocity detonation: D₉₈=1264, D₈₇=1290, D₇₂=1168, and D₃₁=1200 m s⁻¹; the luminescence in the DW almost coincides with the wave front.

Under the same conditions (p₀₀=0.1 MPa and p₀=0.1 MPa), the luminescence behind the wave in the hybrid system (ρ=229 g m⁻³) increases by more than an order of magnitude as compared to the previous case owing to combustion of coal particles. Nevertheless, because of flame separation from the leading SW front in the upper region of the shock tube approximately by 30 cm, coal combustion begins at the same distance and does not provide wave acceleration: D₁₂=1000, D₂₅=882, D₅₆=857, D₇₈=909, and D₈₉=757 m s⁻¹. Flame separation increases with distance, but a gently sloping compression wave with intense luminescence is formed at the tube bottom behind the leading SW front. This compression wave moves toward the leading front and meets the wave reflected from the end face of the shock tube. The reflected wave is a low-velocity DW and moves upward: D₉₈=1337, D₈₇=1429, and D₇₂=1423 m s⁻¹.

In the case of more intense initiation (p₀₀=0.2 MPa and p₀=0.1 MPa), a more powerful blast wave is formed (Figure 5). Detonation with luminescence at the front is formed in the reflected wave close to the tube bottom (Figure 5, c): D₉₈=1369 and D₇₈=1429; the DW velocity close to the top part of the tube is approximately constant: D₆₅=1412, D₅₂=1444, and D₂₁=1500 m s⁻¹.

**Figure 5.** Oscillograms of pressure and luminescence, p₀₀=0.2 MPa, p₀=0.1 MPa, CH₄+10.52 air; D₁₂=1200, D₂₅=1083, D₅₆=1043, D₇₈=930, and D₈₉=927 m s⁻¹.

In the hybrid system (Figure 6), the luminescence behind the wave front drastically increases. A compression wave with luminescence is formed at the tube bottom behind the SW front. The reflected wave is a detonation wave: D₉₈=1983 and D₈₇=2000 m s⁻¹; intense luminescence is observed at the front; the velocities at the top part of the tube are D₆₅=1500, D₅₂=1444, and D₃₁=1500 m s⁻¹.
The coal burns partially; a significant fraction of coal is deposited onto the lower flange. The measurements of the coal mass before and after experiments and the data on the spectral composition show that the burned coal fraction does not exceed 20-30% and depends on the value of $\rho$.

Figure 6. Oscillograms of pressure and luminescence, $p_0=0.2$ MPa, $p_0=0.1$ MPa, CH$_4$+10.52 air–coal dust suspension, $\rho \approx 530$ g m$^{-3}$; $D_{12}=1200$, $D_{25}=1083$, $D_{56}=1043$, $D_{78}=930$, and $D_{89}=927$ m s$^{-1}$.

Conclusions
The parameters and structure of detonation and combustion waves in fuel-lean mixtures of methane with oxygen and air, and also in hybrid systems consisting of a gas mixture and a suspension of fine coal particles were experimentally determined.

Ignition and combustion of coal particles occur behind the combustion, explosion, and detonation wave fronts. An increase in the reaction zone length in gas mixtures leads to enhancement of the degree of coal burning and amplification of compression waves. In hybrid systems, coal combustion competes with methane combustion; there is a minor increase in the detonation parameters and resultant heat release in the reaction zone, and the temperature in the reaction zone increases by less than 15%.

If the incident wave is a decaying explosion wave, then coal combustion is intensified in waves reflected from the end face of the shock tube, and self-sustaining low-velocity detonation regimes may emerge.

The fraction of burned coal in combustion, explosion, and detonation waves does not exceed 20-30%.

References
[1] Wolanski P, Liu J C, Kauffmann C W, Nicholls J A, Sichel M 1988 *Archivum Combustionis* 8 (1) 15-32
[2] Cook P M 1992 *Explosion Gallery*, CSIR Report ENER 93001
[3] Scholl E V, Wymann V 1979 An article from the journal Glucauf-forschungshefte 1 38–46
[4] Dong J, Fan B, Xie B, Ye J 2005 *Proc. of the Combustion Institute* 30 2361–68
[5] Nettleton M *Gaseous detonation: their nature, effects and control* (London, New York: Chapman and Hall) p 255
[6] Pinaev A V, Vasil’ev A A, Pinaev P A 2015 *Shock Waves* 25 (3) 267–5
[7] Vasil’yev A A, Vasil’yev V A 2016 *Vestnik Nauchnogo tsentra po bezopasnosti rabot v ugolnoi promyslennosti - Herald of Safety in Mining Industry Scientific Center. Industrial Safety* Kemerovo ISSN 2072-6534 2 8–39