The influence of coal particles on self-ignition of methane–air mixture at temperatures 950–1200 K

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Abstract. This paper represents experimental investigation of ignition of combustible gaseous mixture with reactive particles in the rapid compression machine at temperatures 950–1200 K and pressures 1.5–2.0 MPa. The experiments were carried out with stoichiometric methane–air mixture in the presence of coal particles with size 20–32 µm. It was found that the presence of these particles not only reduces ignition time but influences on the ignition temperature of mixture. It is ascertained that ignition time of methane in pure air is longer than with same mixture with addition coal dust. This difference is explained to preignition of methane near burning particles. It is shown that ignition of coal dust originates at the temperature of oxidant higher 850 K. Temperature of particles burning in methane–air and air environment heated by compression was measured. The mean temperature is 2500 K. It indicates possibility of premature ignition of gas mixture heated by compression to temperature 1000–1100 K by addition of coal particles.

1. Introduction

Ignition investigation of dispersed systems consisting of reactive particles, gaseous fuel and oxidizer is topical from explosion and fire safety terms, for example in the coal mining industry. There are suspended solids in an atmosphere of coal mines, where methane may contain too. A lot of works have been directed in order to predict ignition conditions, ignition and flame propagation. Much attention is given to formation of dust cloud and initiation of its combustion because of local ignition and propagation of methane combustion wave. Development of this process leads to calamitous consequences. It is known that hybrid mixtures (methane–air–coal dust) are ignited at lower energy of external influence (for example electric spark) than is necessary for ignition of particular suspension of coal particles in the air [1, 2]. Research of this phenomenon is no less interesting from the point of view of process control of the gas mixture ignition. It can become scientific basis to create new modes of traditional fuels combustion. Thereby the purpose of this study is establishment of the possibility to control gas mixture ignition by addition of known reactive particles to the test mixture.

2. Experimental results and discussion

In the study of the reasons of gas mixtures premature self-ignition in the rapid compression machine (RCM) was found that this process is initiated in the separate sites that are formed mainly in the around the burning extraneous particles [3]. It has been very problematic to get
rid of these particles and to carried out experimental measure of delay ignition of reactive gas mixture. The figure 1 shows the pressure change signals in the combustion chamber RCM and photomultiplier (PMT) signals that registered the natural light. These signals were obtained in three experiments with a stoichiometric methane–air mixture at the similar conditions (1.6–1.8 MPa, 1050±10 K). Methane ignition was observed in only one case (the experiment No. 45). The photomultiplier signal of this experiment shows that the relatively low intensity peak with width of 0.5 ms precedes to the main growth light that which corresponds to methane ignition. This light is likely caused by the burning of foreign unknown particle in the test volume.

The PMT signal amplitude from experiment No. 43 does not exceed the noise level. In the experiment No. 46, the PMT has registered more intense glow, however, the ignition of the mixture was not observed. The obtained video frames showed the presence of several burning particles. Thereby there are always some unknown particles in the test volume. And it is practically impossible to get rid of them. Therefore the presence of reactive particles is necessary taken into account. It was found that test mixture does not ignite in all experiments provided thorough cleaning the inner surface of the rapid compression machine and use of piston rings lubrication at decreasing the temperature to 1000 K.

In this way, there was a need to establish a range of conditions, where accelerate of ignition of the gas mixture is possible, i.e. ignition of a mixture by burning particles. In this paper, coal dust at size no more than 32 µm was used as such particles. The sample with mass about 5 mg was evenly sprayed on the inner surface of the combustion chamber and on the front plane of the piston. Stoichiometric methane–air mixture was used as the gas component of the hybrid mixture. Ignition of the coal particles in the synthetic air (20.9% O₂ and 78.1% N₂) was investigated separately. Experiments were conducted in the RCM. During the combustion stroke, gas mixture temperature reached 800–1200 K at pressure 1.5–2.0 MPa. The initial pressure was chosen so to obtain approximately the same molar concentration of oxygen at the end of the compression stroke (4 × 10⁻⁵ mol/m³) at different temperatures. Development of the ignition process was recorded by a high speed camera “LaVision HighSpeed Star X” with a frequency of 12,500 frames per second and a resolution of 1024 × 1024 pixels. Observation was carried out through a quartz window in the end wall of the combustion chamber. The window

**Figure 1.** Pressure (solid lines) and natural light (dashed lines) registered in three experiments (43, 45, 46) for methane–air mixture.
Figure 2. Pressure (I line), natural light (II line), and emission of CH radicals (III line) registered at methane–air–coal dust ignition together with frames from high-speed video. The ignition place is shown by white arrows.

diameter (50 mm) was equal to the diameter of compression cylinder of the RCM. Pressure measurement carried out by the high temperature piezoelectric sensor Kistler 6031U18. Light emission from the test volume was transferred to the two photomultipliers on dual fiber optic cable; the common end of the cable was connected to the quartz window (5 mm dia) in the cylindrical wall of the combustion chamber from the top. Emission of excited CH radicals was separated from the natural light by two narrow-band interference filters (430.4 nm and 430.8 nm, $\Delta \lambda_{0.5} = 2.6$ nm) that were established in front of one of the PMT photocathode. The natural light of the flame during the combustion of methane or coal dust were recorded by the second photomultiplier with spectral sensitivity range is 300–600 nm.

Signals of the pressure sensor and photomultiplier and a eight of frames (time of each is marked by lines on the chart) registered in the experiment with the methane mixture that contains coal dust particles size of 20–32 $\mu$m, are shown on the figure 2. It was found, certain particles ignition occurs yet in the compression process at the temperature about 880 K. During further compression, and increasing the temperature to 1010 K the number of burning particles increases and their combustion continues until the ignition of the methane–air mixture. It is clearly visible on the frames No. 4 and No. 5 that ignition of methane is initiated around of one of the particles.
Figure 3. The conditions of the test mixtures for the study of ignition: 1—methane–air; 2—methane–air–coal dust; 3—and air–coal dust.

At lower temperatures in the end of compression stroke the number of experiments with methane ignition, consisting of the hybrid mixture, decreased. The experiments with coal particles in the synthetic air heated by the compression showed that its ignition occurs at temperatures ranging from 850 K. Herewith, the single burning particles that burn much faster than at more higher temperatures were obtained on the frames. Probably, size of these particles is far less than size of the main parts of the sample that have not been separated by sieving used powder. Generalization of the results of all experiments is shown in the figure 3.

Blacken symbols corresponds to conditions (temperature and pressure), in which methane–air and hybrid mixtures ignite and individual particles of coal dust in the air begin to burn. It is seen that the limited temperature is about 1060 K for ignition of stoichiometric methane–air mixture ignites in the RCM. The ignition of hybrid mixture occurs at temperatures above 1030 K. Thereby, addition of coal particles (20–32 µm) slightly decreases limit temperature of methane ignition in the air. But this difference is within the error estimate of the temperature at the end of compression stroke (less than 5%). It indicates that in experiments without the addition of coal particles, methane ignition was probably initiated by foreign particles. This assumption is based on the video frames obtained in the previous experiments without included coal dust in test volume. Burning particles were found on these frames too.

The possibility of ignition of methane–air mixture by burning coal dust was confirmed with temperature measurement using photoemissive pyrometer. It was installed instead of a high-speed video camera. The luminous flux from the combustion chamber was focused on the photocathode by collimator. Temperature measurement of burning coal particles (20–32 µm) was carried out with a frequency—200 kHz under temperatures: in synthetic air—800–1200 K and methane–air mixture—950–1100 K. The results of these measurements are presented in the
Figure 4. Pressure (black lines—air, gray lines—methane–air) and results of a temperature measurement of coal dust: in air (1) and in methane–air medium (2).

figure 4 at equal temperature of gaseous medium in the end of the compression stroke (1060 K) and molar concentration of oxygen. The coal particles temperatures have been marked by symbols at different time moments in the figure 4 together with the pressure signals (lines in the figure 4). These temperature values are enclosed in the shaded region for clarity. The equilibrium temperature of the products of the reaction of methane with oxygen at a constant pressure is 2700 K. It possesses the lower value than certain values of coal dust temperature. It is seen that the particles temperature is much more than the gas mixture temperature measured at time interval corresponding to the induction period of methane/air mixture. It should be noted that the values of the measured temperatures of the particles in methane/air mixture are in the same range with burning particles temperatures in air. Time average of measured temperature is 2500 K. A similar value was obtained in paper [4] in which larger porous carbon particles were used. These measurements indicate that the burning particles may cause nonuniform temperature distribution in the combustion chamber.

3. Conclusions
In the result of this work, it is shown that the combustion of individual particles of coal dust occurs earlier than the ignition of a stoichiometric methane–air mixture at temperature range from 850 K to 1100 K. As a result, there is the possibility of methane–air mixture ignition by burning coal particles with size 20–32 µm under the temperature 1000–1100 K, that may be the heat source of ignition.
References

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