Auto-ignition of Premixed Methane/air Mixture in the Presence of Dust

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1 Introduction

The some quantity of solid particles is always presented in gas media. At laboratory conditions in contrast to real combustion it is possible to reduce or to control amount and size of the particles in the test volume. For real applications it's necessary to take into account that reactive gas mixture contains solid combustible particles. In several cases effect of the particles presence can become significant. For example, appearance of responsive particles in the chamber of HCCI can localize ignition process and therefore disrupt concept of homogeneous reaction. The other example is a safety of coal mining industry, when combustible dusts and gases are mixed with air and explosion of hybrid mixture can occur. Several studies [1, 2] showed that the hybrid mixtures are more easily ignited than either one component along. Therefore the investigation of ignition of hybrid gas – dusts – air mixtures remains to be important direction for development of new combustion devices as well as for evaluation the hazard of complex explosions in industry. In our rapid compression machine studies of auto-ignition of premixed gaseous fuel - air mixture we found that at temperatures about 1000 K non-uniform ignition is caused by the presence of ultrafine particles [3]. These particles can penetrate into the combustion volume together with test mixture or can be produced by friction between piston seals and cylinder wall during compression stroke. At definite conditions contaminated particles can auto-ignite in the heated gas mixture even earlier than reactive gas component. It causes local decrease of ignition delay and therefore significant deviation of experimental data measured in different tests under the same conditions. It means that time and location of the gas mixture ignition can be controlled by addition of reactive particles. To investigate this phenomenon visualization of direct light emission at auto-ignition process of methane-air, coal dust-air and hybrid mixtures have been performed in this study.

2 Experimental setup

High speed digital imaging has been performed to visualize auto-ignition phenomena of stoichiometric methane - air, coal dust – air and hybrid coal dust – methane - air mixtures at temperatures close to 1000 K and pressures 1-2 MPa. The conditions were generated by rapid compression machine configured on compression ratio about 35. The initial gas pressure and temperature inside compression cylinder and its length were fixed at 12 kPa, 295 K and 779 mm respectively. The combustion chamber height was slightly different from test to test (21.5±0.3 mm) due to technical features of piston stopping and locking mechanism. The chamber is equipped with a high-temperature quartz

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pressure sensor Kistler 6031U18, a gas inlet/outlet valve and quartz window in cylindrical wall (5mm diameter). This window was used for recording the chemiluminescence at ignition and combustion by photomultipliers. Emissions of CH radicals at λ = 431.5 nm were detected by one photomultiplier and the second photomultiplier (the range of spectral sensitivity is 300 – 600 nm) was used for recording total light emission. Gas mixtures were prepared by the method of partial pressures from commercially grade gases of 99.9 % purity and kept during more than 24 hours before study. Coal dust was obtained by sieving of crushed powder of activated carbon. The sieves of mesh size 20 and 32 microns were used. The dust was placed in the combustion chamber by spraying on the walls and the piston head before the experiment.

Direct light emission from test chamber of RCM was visualized by high speed camera “LaVision HighSpeedStar X” at the frame rate 12500 fps and resolution 1024x1024 pixels. The camera was installed in front of compression cylinder at the distance to obtain sharp image at different cross-sections of the combustion chamber. The end of the chamber, the ‘cylinder head’, was fitted with an optically flat, fused silica window (65 mm diameter x 25 mm thick). This window permitted a full view of the chamber cross-section (the diameter of compression cylinder and chamber are equal to 50 mm).

3 Results

The visualization of auto-ignition evolution obtained by high speed camera clearly demonstrates that reaction in methane-air mixture at temperature about 990 K starts from burning particles. The eight frames selected from video are presented on Fig. 1 together with pressure and photomultiplier signals. The corresponded time moment of each frame (exposure time of each is 79 μs) are marked on the plot by vertical lines. Temperature at the end of compression was 990 K. The measured ignition delay time 9.1 ms is sufficiently shorter than predicted one’s from zero-dimensional calculations using well-known kinetic mechanisms GRI 3.0 and Konnov’s (70.9 and 14.7 ms, respectively). Presented images demonstrate initiation of ignition (see frames number 9 and 10 at bottom right corner) at bright spot near the wall. Moreover new ignition kernel appeared also from burning particle (see frames number 11 and 12 at top right corner). The ignition of the particles begins before the end of the compression stroke and lasts until the moment of methane ignition. It correlates well with photomultipliers records. The light emission starts also before the end of compression in a form of separate peaks and the emission of CH radicals begins only with flame appearance (see image number 10).

The intensive motion of burning particles is observed on video. To demonstrate motion to each particle an arrow shows the direction of its movement. The length of each arrow is proportional to the particle velocity. These values were calculated by measurements of particles displacement between two consecutive frames. It is seen that velocities are rather different but not exceed 10 m/s (a mean piston velocity of our RCM is also usually about 10 m/s). The direction of movement is not so different. It is primarily directed along the radius of the chamber but both to it center and from it. Taking into account that we see the projection of particles velocities onto the image plane from all cross-sections of the chamber it is evident that collective displacement of all particles is well agree with the gas motion in the form of a roll-up vortex (Fig. 2). Assuming that burning particles follow gas flow the roll-up vortex structure explains the existence of opposite directed particles movements, the change of magnitude of velocity projection on image plane along chamber radius and the predominant radially direction of all velocities. The a roll-up vortex formation by piston motion is well known [4] and was extensively studied with reference to RCM by experimental visualization methods [5, 6] and CFD calculations [7, 8]. If we will increase the amount of burning particles we can also study aerodynamics in our RCM by observing their movement. This method similar to PIV but is more simple and it is possible to get information from all cross-sections of test chamber at the same time.

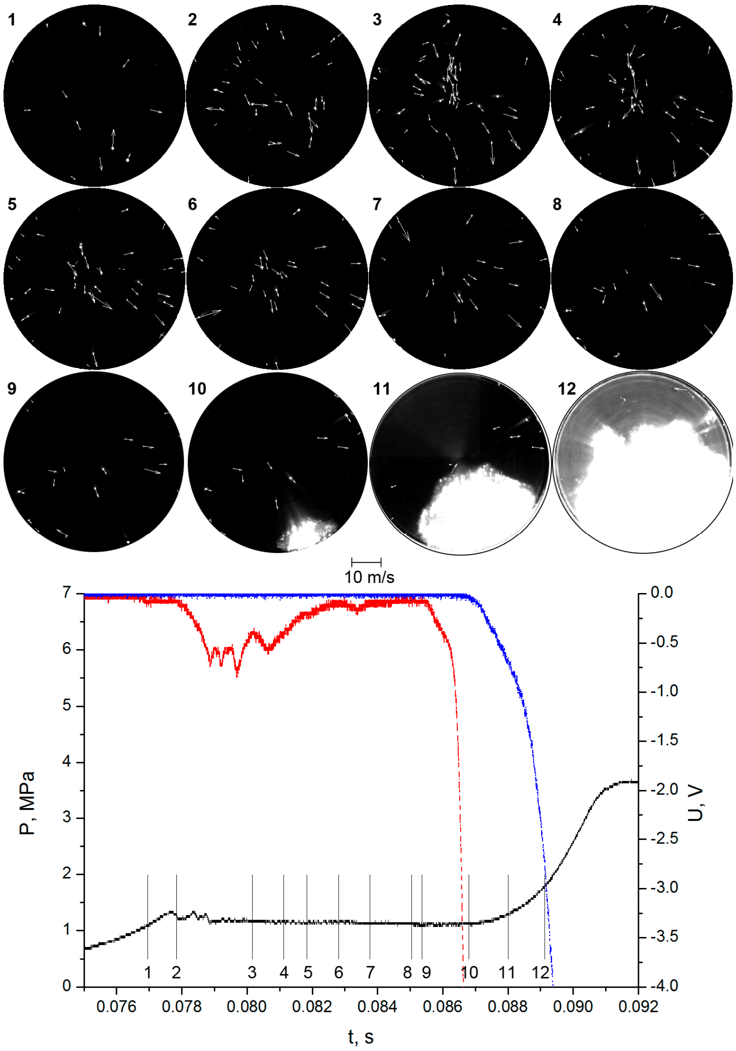
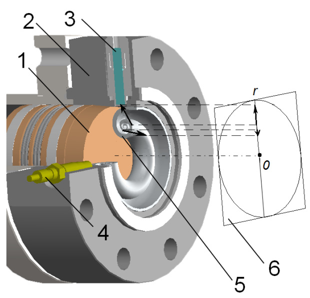


Figure 1. Pressure (black), total light (red) and CH emission (blue line) registered at methane/air mixture ignition together with frames from high speed video



1 - compressing piston,
2 - cylindrical combustion chamber,
3 - quartz window for photometric measurements,
4 - pressure sensor,
5 - roll-up vortex,
6 - the radial velocity projections of particles on image plane

Figure 2. Roll-up vortex formation in test chamber during piston motion

We increase amount of burning particles (trackers) by placing coal particles with diameters 20-32 μm into combustion chamber. This dust is the most suitable as it is easily auto-ignited in heated air and well follow gas flow due to low weight. The example of results obtained from such experiments is presented in Fig. 3, which is an analog of Fig. 1. About 5 mg of coal dust was placed in the combustion chamber. During the test the synthetic air (20.9 % O_2 and 79.1 % N_2) was compressed from initial pressure of 12 kPa. The compression ratio was achieved a little higher (37) than in experiment with methane/air mixture. Therefore the mixture was heated to higher temperature (1130 K at peak of pressure). It is seen from selected frames that some amount of particles starts to burn during air compression at temperature about 860 K (the first image). The amount of burning particles is significantly higher (more than 300 trackers) at the end of compression (image number 6). As for previous case, the majority of particles move along radius of chamber but don't cross it. Near the center velocities of particles decrease to zero and reverse direction.

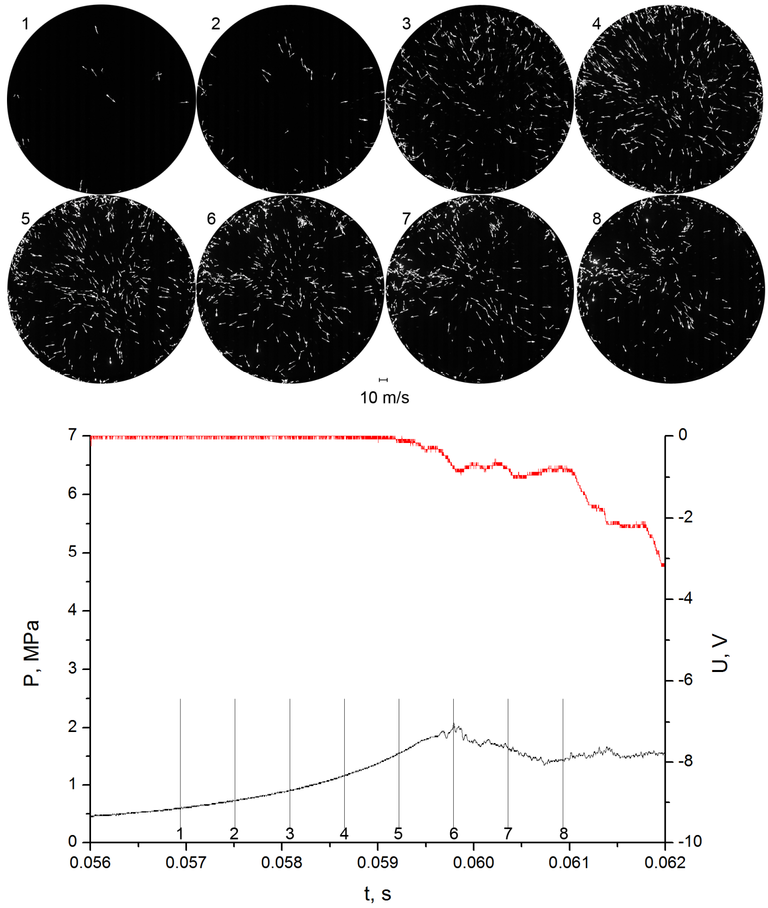


Figure 3. Pressure (black) and total light emission (red line) registered at coal dust/air mixture ignition together with frames from high speed video

To analyze the changes in the structure of gas flow in time we defined the projection of particles velocities on the radius of the combustion chamber and follow their changes in time. The results are presented on Fig. 4 in the form of the distributions of these velocities along the radius at different time moments measured from the end of compression stroke. The positive values are corresponded to velocities that directed to the chamber walls and negative to the center. Each distribution was obtained by treatment of four images i.e. each observation time is 0.24 ms. Therefore for one particle three velocity values can appear at one plot. The first distribution on Fig. 4 shows the low radial velocities only near the center and walls of chamber. Then particles with low radial velocities appear almost on all radii but the density of distribution is not the same. A poorly filled region ("hole") can be found near radius of 20 mm before 1.63 ms to the end of compression. On the following distributions this "hole" rises a little, moves toward the chamber center and disappears at 1.01 ms after the end of compression. The radial velocities distribution becomes almost homogenous. Such evolution of radial velocities distribution demonstrates the moments of formation and dissipation of gas vortex.

This flow visualization technique and analysis can be applied to investigate aerodynamics inside RCM in order to optimize it.

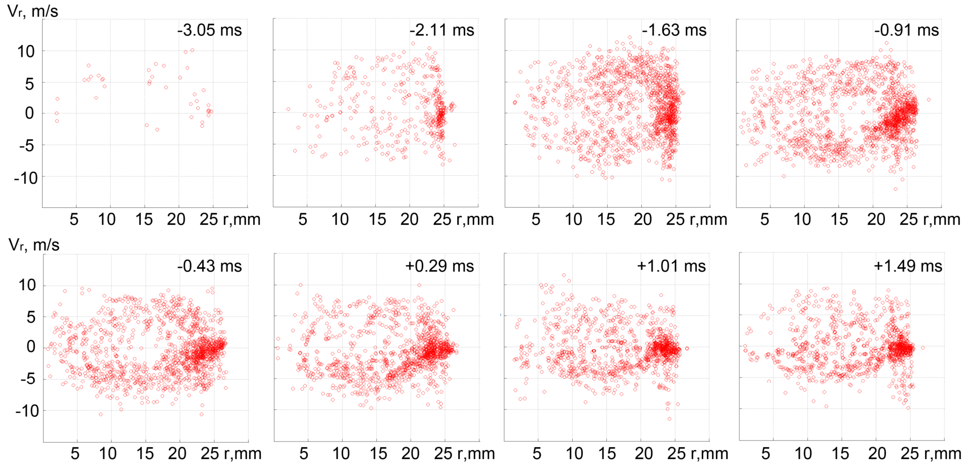


Figure 4. Distribution of radial velocities of the burning particles along chamber radius at different time moments from the end of compression stroke

Finally, experimental results for hybrid coal dust-methane-air mixture presented on Fig. 5.

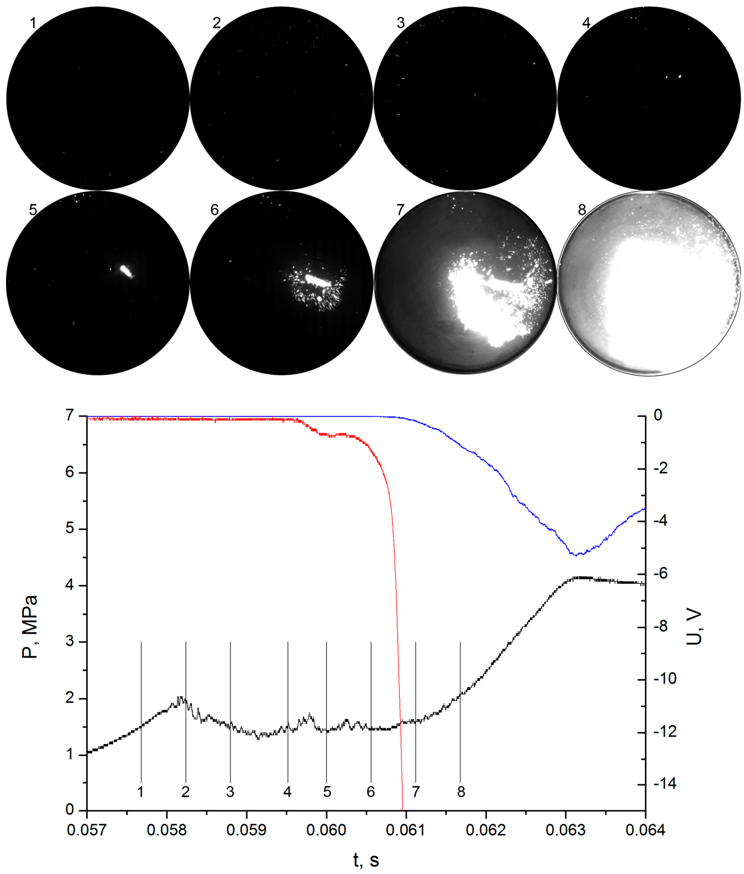


Figure 5. Pressure (black), total light (red) and CH emission (blue line) registered at coal dust/methane air mixture ignition together with frames from high speed video

The same amount of coal dust was placed in chamber of RCM but then it was filled with stoichiometric methane-air mixture. It is seen that ignition of dust particles in heated mixture is not intensive as in pure air. But it is clear that methane ignition started from burning particle (image 6). Photomultiplier signals also demonstrate this: main rise of voltage starts from small peak and then emission of CH radicals appears. The ignition delay of hybrid mixture at 1050 K is three times shorter (3 ms) in comparison with pure methane-air mixture.

4 Conclusion

It was found that at temperatures about 1000 K methane ignition can occur only when some amount of reactive particles are presented in the test volume. The possibility of coal dust to initiate methane ignition was established by experiments with hybrid coal dust – methane - air mixture. Ignition of ultrafine particles occurs early than ignition of methane. At definite conditions it is possible to visualize the gas flow by recording the spatial displacement of individual particles. It was shown that analysis of distribution of radial particles velocities along radius can be used to investigate the dynamics of gas flow structure in RCM at the end of compression stroke. The proposed technique can be applied for optimization of aerodynamics inside RCM.

References

[1] Nagy J, Mitchell DW. (1963) .Experimental coal-dust and gas explosions. (27pp). RI 6344: US Bureau of Mines.

[2] Amyotte PR, Mintz KJ, Pegg MJ, Sun YH. (1993). The ignitability of coal dust–air and methane–coal dust–air mixtures, Fuel, 72: 671.

[3] Krivosheyev PN, Leschevich VV, Penyazkov OG, Shimchenko SYu. (2014). High-speed imaging of premature ignition in rapid compression machine [Advances in Nonequilibrium Processes: Plasma, Combustion, and Atmosphere] Moscow: TORUS PRESS Ltd.: 137.

[4] Tabaczynski RJ, Hoult DP, Keck J. (1970). High Reynolds Number Flow in a Moving Corner. J. Fluid Mech. 42:249.

[5] Strozzi C, Sotton J, Bellenoue M, Mura A. (2007). Self-ignition of a lean methane-air mixture at high pressure in a Rapid Compression Machine. Proc. 3rd Europ. Combust. Meeting, Chiania, Greece.

[6] bGuibert P, Keromnes A, Legros G. (2010). An Experimental investigation of the turbulence effect on the combustion propagation in a Rapid Compression Machine. Flow, Turb. Comb. 84:79.

[7] Lee D, Hochgreb S. (1998). Rapid compression machines: heat transfer and suppression of corner vortex. Comb. Flame 114: 531.

[8] Mittal G, Raju MP, Sung CJ. (2012). Vortex formation in a rapid compression machine: Influence of physical and operating parameters. Fuel 94:409.