Unsteady Propagation of Detonation Wave through the Dust Cloud of Inert Particles

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1 Introduction

One method to reduce shock and detonation waves is the use of the cloud of fine aerosol of water droplets or particles of inert dust (for example, [1]). Attenuation of waves in dusty cloud caused the transfer of thermal and kinetic energy from the gas flow to the solid particles. The important values of such task are concentration of particles, their size, length of cloud.
The aim of this work is studying of the damping of a detonation wave (DW) in a dusty gas and the determination of the critical parameters of a heterogeneous medium, providing complete quenching of waves of detonation and combustion.

2 Experiment

Experiments were carried out in a vertical tube with length of L=7 m and diameter of d=70 mm (Fig.1). The generator of dosed dust (numerated as 12 on Fig.1), based on a solenoid valve with a tapered stem, was located on the top of the tube on its axis. Two trigger sections 11 long by 0.9 m and diameter d_1=50 mm were located near the dust generator arranged symmetrically at some angle to the tube axis. The sensors 8 and 9 for measure of the speed of the wave front (with the data output on an electronic timer 3), piezoelectric transducers 10 to record the value of the pressure profile and the optical fiber photomultiplier tube 7 (PMT) to measure the luminosity profile were mounted along the tube. At the bottom of the tube is also optical section 13. The signals from the piezoelectric and PMT were recorded by two 4-beam oscilloscope 6 (Tektronix). The signals from the piezoelectric gauges read-out to a source-follower amplifier 5 with 10^9 Ohm input resistance (response time of the piezoelectric gauges $\tau \geq 1$ sec). The first base for measuring of pressure profiles has a length of 0.12 m, the second – 2.31 m, the third – 0.20 m, the fourth – 0.57 m.
The sand was used as inert particles, volume V in the container was about 60 cm^3. The results for sand fraction with a particle size of 90÷120 μm was reported in given paper, apparent density δ of this sand fraction was about 1.47 g/cm^3. The free fall of dust in the tube was studied using photomultiplier tubes and LEDs (Light Emission Detector), located in front of the optical fiber PMT. While emptying of the sand container was determined by the PMT waveforms directly to the output of the dust generator. As the sand falls from the tube top, then large sand particles fall faster ones, dust volumetric density

changes in a cloud and a division of the particle size is observed. The trailing edge of the dust cloud has a greater length than the front. The level of half-light intensity determines the position and size of tighter "core" dust veil, and the total length of the initial and final sections of the less dense veil. Based on these dimensions, the average volumetric dust concentration were determined for the "core" – $2.3 \le \rho_1 \le 4.0$ g/l, and for dust – $2.2 \le \rho \le 3.5$ g/l.

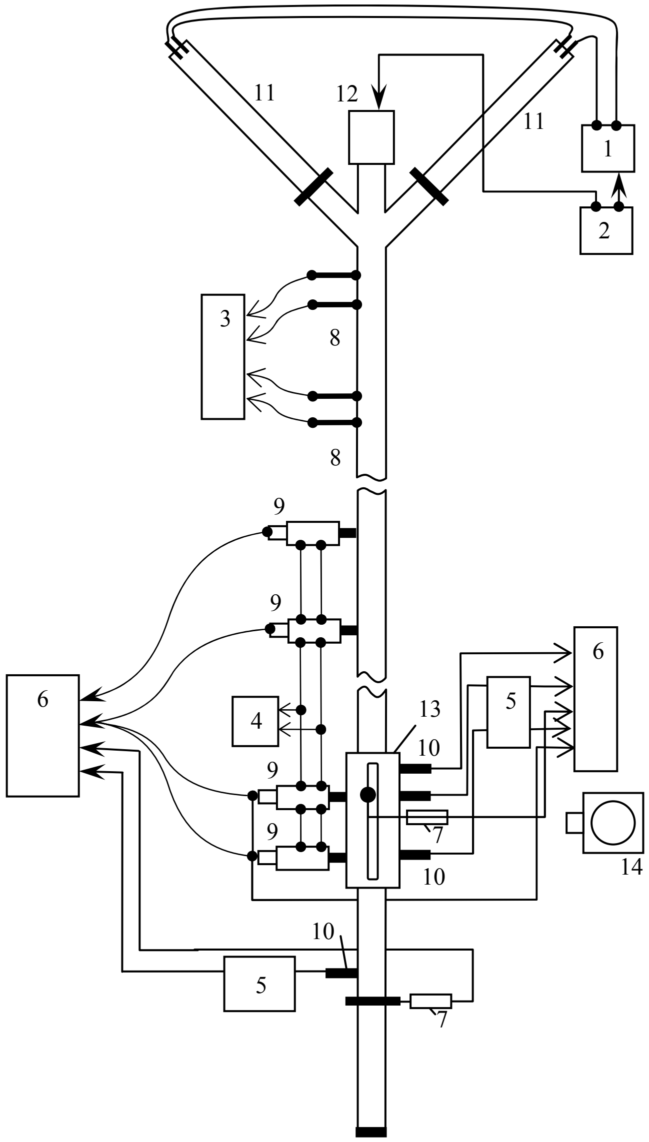

Figure 1. The scheme of experimental device: 1 – high voltage source, 2 – electronic timer, 3 – digital chronometer, 4 – dc voltage source, 5 – source-follower amplifier, 6 – oscillograph, 7 – secondary emission photocell, 8 – piezoelectric sensors for measure of wave velocity, 9 – ionization gauges, 10 – piezoelectric sensors for measure of pressure, 11 – initiation section, 12 – generator of dust cloud, 13 – optical section with transparent windows, 14 – photo-camera.

The time when the dust reaches the end of the tube, the length of the veil and the length of free dust zone near the tube top were determined. The moment in time when a dust cloud reaches the lower end of the tube, was chosen as the initiation moment of the detonation process in the test gas mixture at the top of the tube. Tube before the experiment was pumped by vacuum pump and filled with investigated gas mixture $CH_4+2O_2+N_2$. To accelerate the transition from deflagration to detonation and successful formation of steady DW, the initiation sections were filled with a mixture of C_2H_2+2.5O_2. Detonation initiation was carried out by electric spark from a high voltage source. For CH_4+2O_2+N_2 under normal conditions the calculated detonation velocity D=2225 m/s, the cell size $a \approx 4$ mm. The dust concentration varied both by the amount of dust at a fixed pressure of the mixture, and by varying the initial pressure at a fixed mass of dust (with a decrease in the initial pressure the large mass of inert dust is involved in the reaction zone).

3 Results

The results of measuring of the DW velocity D in the gas showed that the wave enters the steady

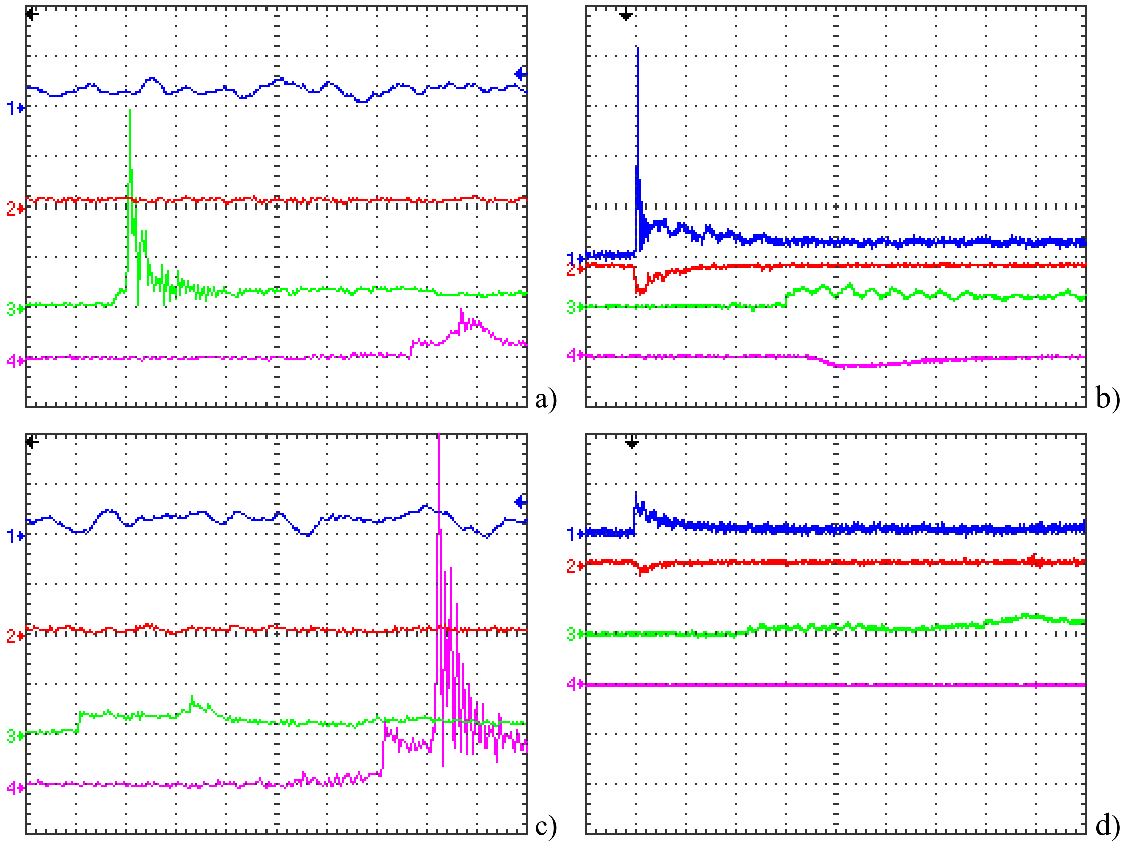

Figure 2. Pressure oscillograms (a - traces 1-4; b, d - traces 1,3;) and emission (b, d - traces 2,4) in DW of the gas mixture CH4+2O2+N2, p0=0.015 MPa, dust size δ = 90÷120 micron, V = 30 cm3 (a, b) and 40 (c, d). Horizontal - 25 (a, c), 250 (b), 500 (d) μs/div. Vertical - a) 1 - 500 mV/div (3.61 MPa/div), 2 - 100 mV/div (4.44 MPa/div), 3 - 20 mV/div (4.76 MPa/div), 4 - 50 mV/div (5.64 MPa/div), b) 1 - 10 mV/div(2.38 MPa/div), 2 - 500 mV/div, 3 - 50 mV/div (2.68 MPa/div), 4 - 200 mV/div; c) 1 - 500 mV/div (3.61 MPa/div), 2 - 100 mV/div (4.44 MPa/div), 3 - 20 mV/div (4.76 MPa/div), 4 - 20 mV/div (2.26 MPa/div), d) 1 - 10 mV/div (2.38 MPa/div), 2 - 500 mV/div, 3 - 50 mV/div (2.68 MPa/div), 4 - 200 mV/div.

detonation (2240÷2200 m/s) at a distance of 2 m from the top of the tube. The wave velocity has deficit about 1% in compared with the Chapman-Jouguet value. The steady DW then goes into a dust veil.

Figure 2 shows the pressure and emission profiles in DW at p_0 = 0.015 MPa, a, b – the same experience with the initial volume of sand V = 30 cm^3, d – experiments with V = 40 cm^3.

The velocity of the wave is attenuated (a, b) with 2036 m/s (top tube) to D_1 = 1935 m/s, D_2 = 1540 m/s, D_3 = 1429 m/s, D_4 = 1013 m/s as it moves to the dust veil. Wave profile is changed from detonation to a rectangular shock. The luminescence intensity in the fine fraction has fallen markedly.

The weak luminescence is observed behind shock wave (Figure 2,b). The sensor PD4 fixed the secondary detonation behind the leading front in experiment (shown in Figure 2), spreading at velocity of D_3 = 1307 m/s. Wave re-accelerated firstly, but then again slowed to D_4 = 1262 m/s. The slow characteristic of wave in the experiment in Figure 2,d went smoothly: D_1 = 1412 m/s, D_2 = 1448 m/s, D_3 = 909 m/s, D_4 = 681 m/s, the glow disappeared.
Experiments with p_0 = 0.01 MPa (Figure 3a, b) showed complete attenuation of detonation and combustion waves: from 2160–2190 m/s (the upper portion of the tube), the wave decays to D_1 = 1600–1090, then D_2 = 592–462, D_3 = 690–570, D_4 = 100–310 m/s.

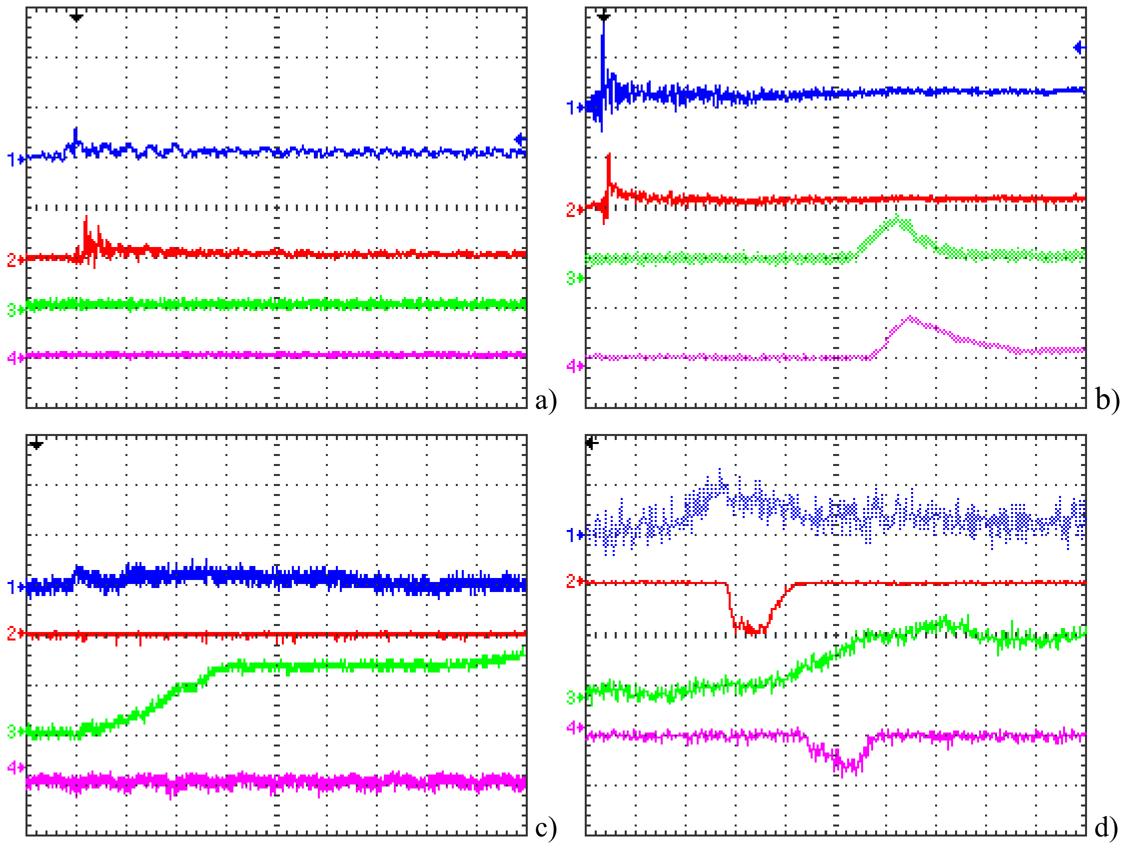

Figure 3. Pressure oscillograms (a, b - traces 1-4; d - traces 1, 3;) and emission (c, d - traces 2, 4) in DW of the mixture $CH_4+2O_2+N_2$, p_0=0.01 MPa, dusty veil δ=90÷120 μm, V = 50 (a-c), 60 (d) cm^3. Horizontal - 250 (a), 1000 (b), 10000 (c), 2500 (d) μs/div. Vertical - a) 1 - 1 V/div (7.22 MPa/div), 2 - 50 mV/div (2.22 MPa/div), 3 - 10 mV/div (2.38 MPa/div), 4 - 20 mV/div (2.26 MPa/div), b) 1 - 500 mV/div (3.61 MPa/div), 2 - 20 mV/div (0.89 MPa/div), 3 - 5 mV/div (1.19 MPa/div), 4 - 10 mV/div (1.13 MPa/div), c) 1 - 5 mV/div (1.19 MPa/div), 2 - 50 mV/div, 3 - 10 mV/div (0.54 MPa/div), 4 - 20 mV/div, d) 1 - 2 mV/div (0.48 MPa/div), 2 - 2 V/div, 3 - 5 mV/div (0.27 MPa/div), 4 - 20 mV/div.

As a result, it was found that after the DW attenuation (Figure 3, the numbers 1, 2) on the lower measuring section the pressure wave with an amplitude of 0.08 MPa was propagated (Figure 3b, the numbers 3, 4). Luminescence intensity in this wave (Fig. 3d, traces 2 and 4) is an order of magnitude less than the detonation wave decays recorded in the optical section (in these experiments the darkening filters were used to provide a linear operating characteristic of PMT at a relatively high level of the luminosity from the detonation wave). In experiments b, d (Figure 3) the sensitivity of the oscilloscope channels to record the signals from piezoelectric and PMT was increased, also was increased the length of time base, darkening filters are removed from both the PMT.
Record signals on long scanning showed that after reflection of weak pressure waves from the end, secondary ignition of unburned products not observed, the luminosity is completely absent.

The dependences of wave velocity along distance of dust cloud are presented on Figure 4 (for conditions of Figs.2 and 3). It was seen, that the wave velocity demonstrates the unusual behavior in dust cloud: the wave tries to regenerate and accelerate on some distance instead of monotonic failure (up to distance of 5 m along the tube). Increasing of sand concentration tend to higher failure of detonation and combustion waves.

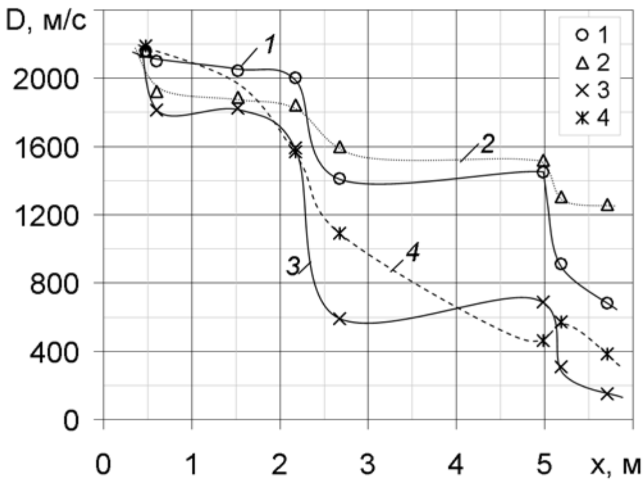

Figure 4. Failure of detonation wave in powder cloud (vertical axis – wave velocity m/s, horizontal axis – distance along tube axis in m. Symbols 1 ÷ 4 correlate with experiments on Fig.2d,c and Fig.3c,b.

The photographs of inert particles in initial state and after influence of detonation wave are illustrated on Fig.5.

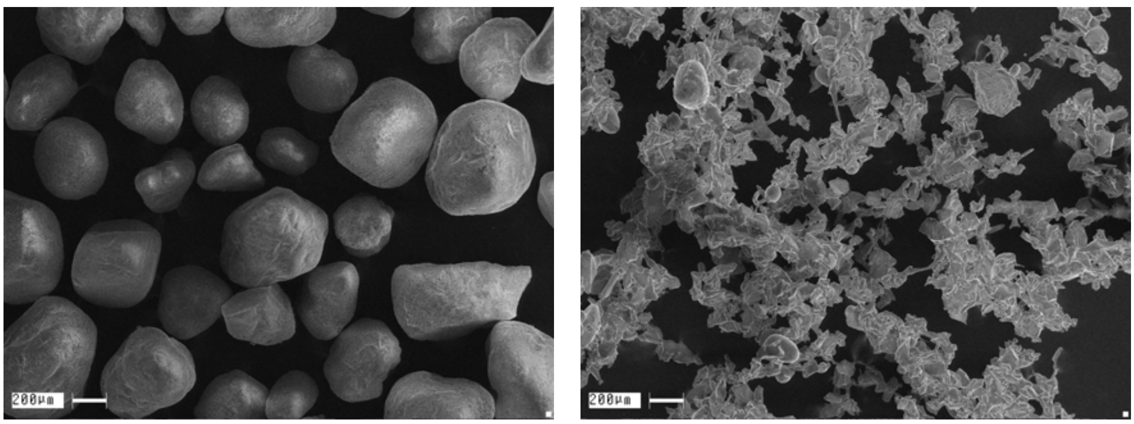

Figure 5. Photo of initial dust particles (left) and particles after influence of DW (right).

4 Conclusion

To dampen the steady detonation in a mixture of $CH_4 + O_2 + N_2$ at a pressure 0.01 MPa, the complete attenuation of the wave of detonation and of combustion in a dusty veil of sand with particles of 90 ÷ 120 microns was observed at volumetric average dust concentration of about 2.5 g/l on a length of about 6 m.

The presence of dust in the gas mixture leads to a change in the mechanism of ignition on detonation front, because there are additional hot spots due to the deceleration of the gas flow on the particles. This can lead to a secondary detonation in a dusty environment and slow down the decay of the detonation wave.

In a homogeneous environment the burning of the mixture is carried out in the transverse waves behind the leading front of gas detonation, which form a cellular structure. In the presence of solid particles a local increase in temperature of the gas at gas braking will lead to the fact that apart from the transverse waves the additional centers of mixture ignition in the vicinity of the particles will be appeared. As increasing of the number of particles (volumetric average dust density) the continuous leading front of ignition of the gas mixture seems restructuring detonation wave.

References

[1] Fedorov AV, Fomin PA, Fomin VM, Chen JR. (2011). Mathematical Modeling of Detonation Damping by Cloud of Small Particles (in Russian). ITAM SB RAS – SibStrin, 156 pages, ISBN 978-5-7795-0517-8.