EXPERIMENTAL STUDY OF EXPLOSION WAVE PROPAGATION IN HYDROGEN-AIR MIXTURES OF VARIABLE COMPOSITIONS

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ABSTRACT

Results are given of experimental study of propagation of explosion waves in hydrogen-air mixtures of different compositions under conditions of cumulation. The investigations are performed in a setup consisting of two parts, namely, the upper part in the form of a metal cone and the lower part in the form of a rubber envelope hermetically attached to the cone. The upper and lower parts of the experimental setup are separated by a thin rubber film and may be filled with hydrogen-air mixtures of different compositions.

INTRODUCTION

For successfully solving the problem of safe handling of hydrogen, one must study the most hazardous modes of combustion of hydrogen-air mixtures. Such modes include those of non-stationary combustion. Especially high loads are observed in the case of emergence of unsteady combustion in cumulating devices. In their presentation to the ICHS 2007, the authors demonstrated that the emergence of unsteady combustion of hydrogen-air mixtures in the conic element may cause the development of extremely high pressures at its apex [1]. These results were obtained in the Konus setup (Fig. 1). The Konus setup consists of two parts. The upper part, i.e., a metal conic element with the apex angle of 60º, and the lower part, i.e., a rubber envelope, make up a hermetic volume filled with the mixture under investigation. The mixture is ignited in the bottom part of the rubber envelope.

The investigation of cumulation of explosion wave (performed in the cone element) propagating in a uniformly mixed combustible gas mixture revealed that the values of pressure observed in the cone are not the values of pressure arising as a result of steady detonation under conditions of cumulation. More dangerous and significant as regards their force action on the structural elements are unsteady combustion modes. The instability of the front of unsteady combustion is one of the reasons for the emergence of perturbations, waves, and flows in the medium before the front. The intensification of waves in closed and cumulating volumes leads to the emergence of secondary combustion sites, i.e., explosions, the parameters of which exceed the values predicted by the Chapman--Jouguet conditions for steady detonation by a factor of approximately five and may be as high as 100 MPa. In so doing, the experiment reveals that explosions in large closed volumes and in volumes which cumulate waves and perturbations may occur at a low energy of initiation (lower than critical by an order of magnitude).

A significant pressure increase is observed in cumulating volumes filled with combustible mixture without the emergence of secondary combustion and explosion in cumulation zones. The pressure increases as a result of intensification of explosion waves maintained by weak primary combustion. The value of pressure, registered in our experiments in modes without secondary combustion in the cumulation zone, was two to five times higher than that arising in the case of cumulation of waves as a result of explosion of the same explosive charge in a neutral medium. These results were obtained for uniformly stirred mixtures. In practice, one most frequently has to deal with inadequately stirred mixtures.

For unstirred hydrogen-air mixture, the development of combustion and explosion is possible in a volume in which the average concentration of hydrogen is lower than the concentration limit of supersonic combustion.

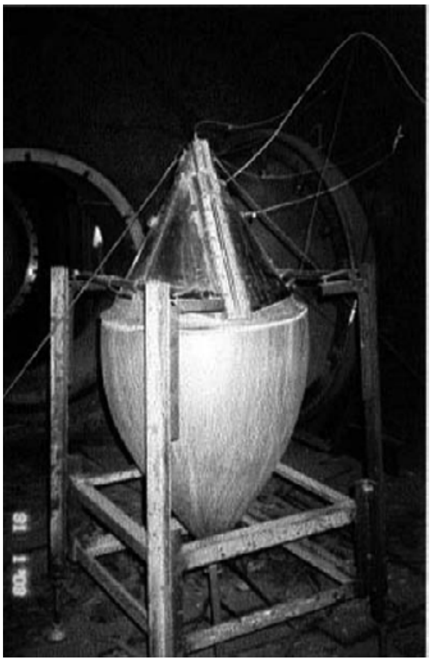

Figure 1. General view of Konus setup.

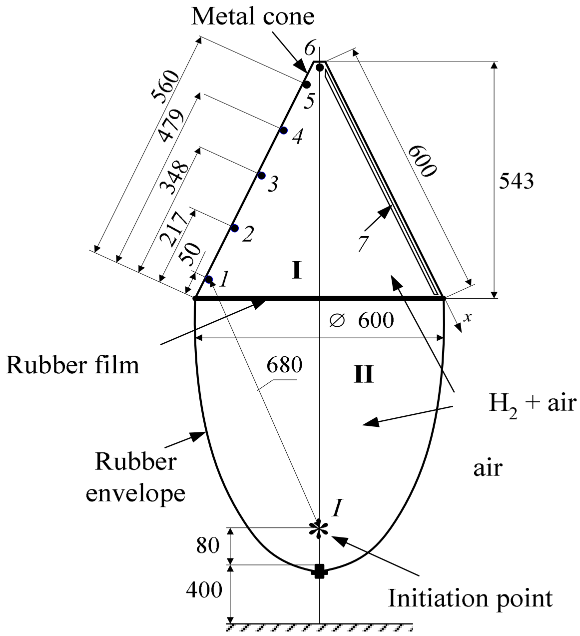

Figure 2. Scheme of Konus-2 setup.
1-6 – pressure sensors, *7* – slit inspection window for high-speed photography (all dimensions are in millimeters)

In this study, we simulated the emergence of unsteady combustion of unstirred hydrogen-air mixtures under conditions of cumulation.

UNSTEADY COMBUSTION OF UNSTIRRED HYDROGEN-AIR MIXTURES

This process was studied in the Konus-2 setup, which differed from the Konus setup in that the upper and lower parts of the setup were separated by a thin film and filled with hydrogen-air mixtures of different compositions (scheme of the two-chamber version of the setup is given in Fig. 2). The concentration of hydrogen in the mixture was varied from 9 to 40% by volume both in the cone and in the rubber envelope. The process was initiated at point *I* by blasting a charge of PETN (Pentaerythritol tetranitrate) or RDX (Cyclotrimethylenetrinitramine) by way of exploding a copper wire 0.05 mm in diameter. The wire explosion energy was 6 J. The experiments involved measuring the pressure on the cone generatrix at points of location of sensors and recording the times of reaching pressure extrema relative to the instant of initiation of the process. Pulsed pressure sensors (PCB Piezotronics) were used. The time scan of proper glow of combustion front was obtained for a number of modes, which was recorded via slit inspection window of the cone generatrix.

For determining the impact made on the experimental results by the rubber film separating the volumes, experiments were performed in which the cumulation was investigated in the two-chamber mode with both volumes filled with a stoichiometric mixture. These data are compared in Table 1 with the results for mixtures of the same composition in the volume without the film.

The change of experimental conditions (transition from single-chamber to two-chamber mode) affects, first of all, the time characteristics of the processes: an increase was observed of the time intervals from the instant of initiation to that of recording of pressure extrema on both transducer *1* (t_1) and transducer *6* (t_6). Both these values are indicative of the development of the process in the rubber envelope, of the time of interaction of the “wave packet” propagating before the primary combustion front with the film, and of the development of cumulation in the hard cone. The duration of the process of cumulation in the cone corresponds to the time interval between the instants t_6 and t_1, and the increase in this time interval indicates that the process of cumulation in the two-chamber mode turns out to be significantly longer.

A longer (by a factor of ~1.3) time of signal delivery to sensor *1* is observed in two-chamber modes compared to single-chamber ones, as well as the difference (by ~65%) between the maximal pressures in the process of cumulation at sensors *2–4*.

Table 1. Comparison of two-chamber and single-chamber modes.

Mode	Pressure value *P*, MPa, & registration time *t*, μs *					
	Sensor, No.					
	1	2	3	4	5	6
two-chamber	3.67 (428)	1.39 (520)	1.44 (628)	1.68 (740)	9.40 (769)	131.60 (820)
	2.33 (408)	1.48 (540)	4.30 (624)	2.73 (680)	5.42 (728)	55.31 (740)
	2.44 (400)	1.93 (448)	2.99 (588)	2.07 (632)	8.87 (700)	80.57(708)
single-chamber	5.40 (348)	4.94 (400)	4.68 (448)	3.89 (504)	3.86 (538)	86.20 (556)

*Note: * Here and in the other tables there are the times of reaching pressure extrema relative to the instant of initiation of the process in the brackets.*

Figure 3 gives oscillograms recorded in the experiment performed for the mode in which the film separated the mixture containing 17% hydrogen in air (in the cone) and the stoichiometric mixture (in the rubber envelope). The lean mixture was placed in the hard cone, and the stoichiometric mixture – in the volume which is bounded by the soft envelope under the cone (see Fig. 2). The signals are given which were recorded by sensors *1–6*. The maximal pressure at the apex in this experiment was 79.48 MPa, and the instant of time when it was registered relative to the instant of initiation was 780 μs.

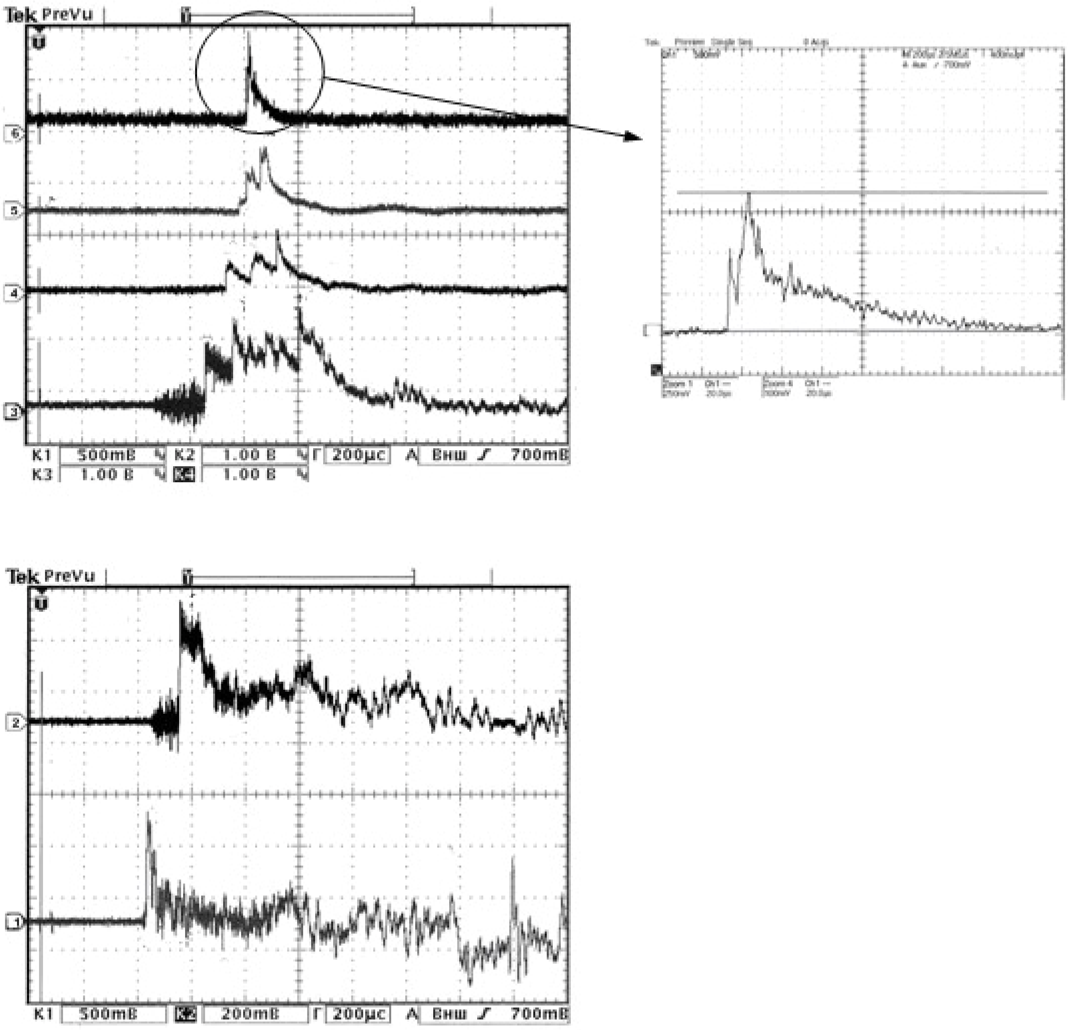

Figure 3. Oscillograms of pressure sensor signals.
Two-chamber mode, in the cone –17% H_2+air; in the rubber envelope – stoichiometric mixture.
At upper right –oscillogram of signal of sensor *6* with increased time resolution.

Three series of experiments were performed in the Konus-2 setup for simulating unsteady combustion in hydrogen-air mixtures of different compositions. In the first series of experiments, the rubber envelope contained a stoichiometric hydrogen-air mixture, and the composition of mixture within the cone was varied from experiment to experiment from 9 to 30% by volume. The experimentally obtained pressures in the cone apex for this series are shown in Fig. 4. Table 2 gives the results from this series for lean mixtures. In the second series of experiments, the metal cone contained air, and the hydrogen concentration in the rubber envelope was varied from 9 to 40% by volume. In the third series of experiments, the metal cone contained the stoichiometric hydrogen-air mixture, and the hydrogen concentration in the rubber envelope was varied from 17 to 29% by volume. Typical results of experiments in this series are given in Table 3. The results of the third series of experiments are also given in Fig. 5.

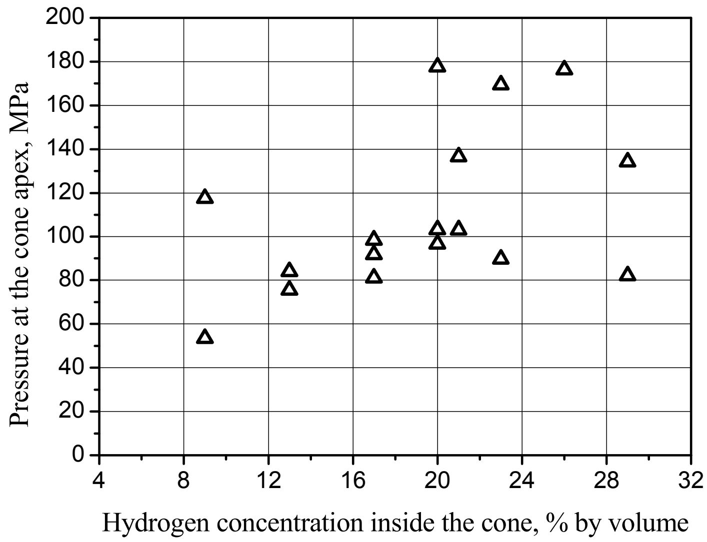

Figure 4. The experimentally obtained pressures in the cone apex for the first series of experiments. The rubber envelope contained a stoichiometric hydrogen-air mixture.

Table 2. Typical results for modes with a stoichiometric mixture in the rubber envelope and lean mixture in the cone. Initiation of the process was made by blasting 0.8 g PETN.

Concentration of H_2 in the cone, % vol.	Pressure value P, MPa, & registration time t, μs					
	Sensor, No.					
	1	2	3	4	5	6
9	2.14 (394) 1.90 (448)**	–	1.77 (632) 1.04 (992)* 1.58 (1130)*	1.41 (748) 4.67 (884)* 5.95 (984)*	11.67 (832) 14.73 (900)*	115.19 (836)
	2.30 (440)	1.26 (558)	1.15 (680) 1.28 (996)* 1.95 (1150)*	1.61 (780) 4.29 (904)* 5.87 (1030)*	11.75 (860) 14.20 (944)*	52.49 (872)
17	2.85 (392)	1.46 (532)	1.54 (632)	1.61 (728)	11.54 (800)	97.69 (808)
	2.41 (384)	1.37 (510)	1.25 (649)	1.47 (744)	7.01 (840)	52.41 (948)
20	6.20 (414)	0.41 (532)	1.73 (644)	1.54 (732)	8.78 (784)	174.17 (808)
	3.05 (396)	1.82 (528)	2.10 (632)	1.61 (724)	7.01 (784)	94.63 (812)

*Notes: * Pressure in return flows.*

*** The second extreme on the pressure oscillogram.*

The experiments performed in tubes revealed that the mixture containing 9% by volume hydrogen in air is explosion-proof, and that no steady-state detonation mode of combustion is observed under normal initial conditions in a mixture containing ~17% by volume hydrogen [2]. In our experiments, the high pressure was caused by the explosion of mixture in the cone apex. The experimental data given in Table 2 and obtained when filling the hard cone with a hydrogen-air mixture, the hydrogen concentration in which is lower than the lower limit of detonation, demonstrate that an explosion occurs under conditions simulated by us; this is indicative of the scale of explosion hazard in reaction volumes and rooms filled with incompletely stirred lean combustible mixture.

In the first series of experiments (with stoichiometric mixture in the rubber envelope and different compositions in the cone, Table 2), the pressures at the cone apex in individual experiments reached high values; for some lean compositions with 20% by volume hydrogen, the maximal pressures of 174.17 MPa obtained in our investigations were registered, including the investigations in single-chamber modes for stoichiometric mixtures. This fact calls for further investigation.

In the experiments where the cone contained air, and the composition of mixture in the rubber envelope was varied (the second series), results were obtained in which the pressures likewise exhibit significant values.

Table 3. Typical results for modes with a stoichiometric mixture in the cone and variable mixtures in the rubber envelope. Initiation of the process was made by blasting 0.8 g PETN.

Concentration of H_2 in the rubber envelope, % vol.	Pressure value P, MPa, & registration time t, μs					
	Sensor, No.					
	1	2	3	4	5	6
17	0.16 (1020)	0.15 (1290)	0.21 (1510)	0.22 (1710)	0.54 (1930)	2.50 (1950)
20	0.27 (1310)	0.27 (1580)	0.24 (1460)	0.29 (1660)	1.00 (1860)	3.64 (1890)
23	0.28 (992)	0.27(1240)	0.24 (1460)	0.28 (1670)	0.70 (1870)	3.64 (1890)
23	0.30 (746)	–	0.37 (1180)	0.30 (1360)	–	10.94 (1560)
24	0.42 (812)	0.46 (1040)	0.38 (1210)	0.37 (1400)	1.67 (1560)	9.99 (1580)
25	1.19 (414)	2.59 (556)	–	–	–	20.41 (794.4)

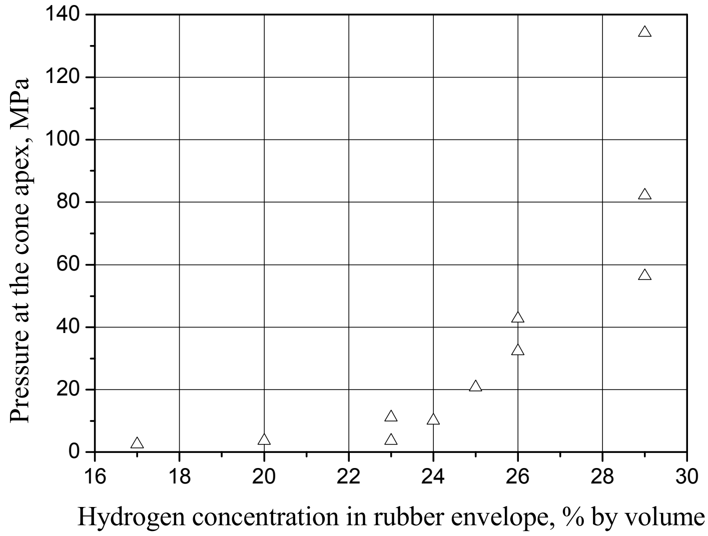

Figure 5. Maximum pressure as a function of H_2 concentration in the rubber envelope. Concentration of H_2 in the cone is equal 29% by volume. Initiation was made by blasting 0.8 g of PETN.

At low concentrations of H_2 (17 to 23% by volume) in the rubber envelope, the values of pressure at the cone apex are low and comparable with those obtained under conditions of single-chamber mode with the entire reaction volume filled with a mixture of the same composition as that in the rubber envelope.

The values of pressure registered at the cone apex markedly increase with increasing concentration of H_2 (above 23% by volume) in the rubber envelope.

Apparently, the correlation between the time characteristics of gas-kinetic parameters in the zone of cumulation, which are characterized by the parameter τ_{gk}, and the times τ_{gd}, during which the high values of gasdynamic parameters (temperature and pressure) are retained in this zone, fails to provide for the possibility of explosion, namely, $\tau_{gd} < \tau_{gk}$ (the correlation is known as the 1st Damköhler criterion), which may explain the low values of pressure registered in this series of experiments.

CONCLUSIONS

1. An experimental simulation was performed of combustion of unstirred hydrogen-air mixtures in cumulating volumes.

2. It is demonstrated that, in the case of unstirred hydrogen-air mixtures, the combustion and explosion may develop even in a volume in which the concentration of hydrogen is lower than the lower concentration limit of detonation.

3. Under conditions of combustion of unstirred hydrogen-air mixtures, higher pressures develop during the motion of the combustion front from the regions filled with rich mixtures to those with lean mixtures.

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