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ON CONDITIONS ENABLING RESONANT COMBUSTION IN GAS EXPLOSION IN NON-ENCLOSED VOLUME

It has been observed, that resonant combustion may develop in gas explosions taking place in chambers with light relief panel after the panel is removed. It has been noted, that initiation of the resonant combustion coincides with the moment of the combustion wave approaching the chamber walls. It has been found out that the location of the ignition point has a great influence over the oscillation intensity: when the ignition happens closer to the center of the chamber, the amplitude increases and may reach the values that are from 5 to 10 times higher than the panel removal pressure, thus signifying the resonant combustion as a highly hazardous factor.

Keywords: gas explosions; resonant combustion; hazard; physical experiment; ignition point.

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Introduction. Rationale

Statistics shows that over 95 % of gas explosions take place in households [1]. This circumstance is notable, as an explosion in domestic space has characteristic development conditions, primarily because the explosion takes place in relatively small rooms that have a limited variety of forms. Information in regulatory documents (including the fundamental ones, such as GOST R 12.3.047–2012, BS EN 14994:2007, NFPA 68) and published papers covering risk reduction for possible gas explosion in such premises amounts to a recommendation to use windows as relief structures (RS) that are destructible when the pressure inside increases, thus providing connection of the inner volume with the atmosphere. Recommendations in these standards are based upon studies of explosions with ignition of *gas-air* mixture in the middle of approximately cubic rooms. They also have corrections for flame-generated turbulence in case of explosion at premises with the form deviating from cubic one, etc. [2–9]. Only GOST R 12.3.047 passingly mentions a possible influence of resonant combustion and only. At that, development of this variant of explosion is linked with the relief structure removal speed: *"momentary" breaking of relief section increases probability of resonant combustion arising inside the apparatus. Amplitude in the acoustic wave of resonant combustion may attain ±0.1 MPa. Actuating the mixture, e. g., with a fan during the development of the explosion leads to decrease in amplitude of pressure oscillations*…". It should be noted, that the value of pressure stated in this quotation is more than an order of magnitude higher than the allowable pressure indoors and only for premises that are in category A or B of fire-explosion safety. The document mentions no other factors influencing appearance and development of resonant combustion other than momentary breaking and actuating the mixture. Nevertheless, this statement puts the efficiency of fire and explosion safety measures in question, if they do not cover development of this dangerous type of combustion.

Answering the question whether the resonant combustion is possible in gas explosions in residential properties, let us note that the experimentally registered events of resonant combustion refer to volumes that are close to those of residential properties [10, 11]. It gives us ground to suppose that such phenomenon may take place in real life.

Resonant combustion in brief

The first reports of resonant combustion as a laboratory effect date back to the times of Higgins and Rijke (XIX century) [12]. Appearance of this effect is known from publications that analyzed burning of hydrocarbon fuels in industrial furnaces and combustion chambers of aircraft and rocket engines. In some cases the resonant combustion was marked as a problem [12, 13], as it leads to destruction of the structure, in others — as a way to boost the combustion process [14]. Let us note that in those cases there was a combustion with a stationary or quazistationary nature. Gas explosion, which lasts for less than one second and has a pronouncedly non-stationary nature, is a different story. In turns out that during this fast process, under certain conditions the resonant combustion may develop as well, as it is evident from experiments conducted both in Russia [10] and abroad [11]. According to the results of these experiments, under resonant combustion conditions, both amplitude of oscillations and the average explosion pressure underwent abrupt increase (sometimes severalfold) in comparison to a regular explosion, which is not only supportive of the quote above, but also extends the hazard boundary. With respect to real-life situations, it means that, on the one hand, the hazard of building destruction and both loss of life and loss of property risks are significantly higher than those stated in the regulations, and on the other hand, that studying the resonant combustion in gas explosions shall be seen as a viable problem.

On possibility of predicting the resonant combustion

Is there a resonant combustion mode in real-life domestic gas explosions? This thesis is impossible to contest, neither support, as the residential accommodations are not equipped with modern means of measurement and recording.

It is virtually impossible to predict appearance and development of the resonant combustion from mathematical models that were created before the rise of computers and digital technologies and based upon feedback mechanism [12–14]. This is primarily due to the fact that the oscillations that develop during the resonant combustion have non-linear characteristics and mechanisms of their actuation are also exclusively non-linear. In short, they are self-sustained oscillations. During those years, the equations used for process description were almost exclusively linear, or, if absolutely necessary those of low non-linearity. It is also not the only cause. The thing is, acoustic oscillations appearing in the resonant combustion are a process with distributed parameters and they may be described with partial differential equations, which may be solved only numerically. Currently, there are great hopes for *CFD* (Computational Fluid Dynamics) numerical methods, however as of now these hopes have been fruitless, as one group of authors failed to describe these self-sustained oscillations using the methods [15–17], while another group of authors succeeded only after marking the oscillating contours [18, 19].

Nevertheless, the authors of [8] succeeded in modeling acoustic oscillation excitation when describing a gas explosion in a cylindrical tube while applying the large-particle method having been developed in Russia [21]. At that, the system of equations used to describe the explosive development did not have any feedback loops: they appeared on their own, as a result of evolution of the solution. Unfortunately, self-sustained oscillations are still not described for volumes similar to those of accommodation spaces.

Naturally, to study the resonant combustion process we shall select an expensive and inefficient experimental method, aiming at thoroughly looking through each factor that may influence the resonant combustion development under gas explosion conditions.

This paper studies influence of the stoichiometric mixture ignition point location in open volume with a size and form close to those of real-life accommodations.

Experimental means

Test bench. The experiment was carried out at the premises of Moscow State Construction University's Institute of Complex Construction Safety with the help of a cubic explosion chamber with the volume of 10 m^3, complying with the requirements of GOST R 56289–2014 and provided with a relief window with the area of 2 m^2 (Fig. 1) [20]. Propane was fed into the chamber until a mixture with air close to stoichoimetric was obtained. Inside the chamber, there was a fan for mixture agitation and an ignition device. During the experiment,

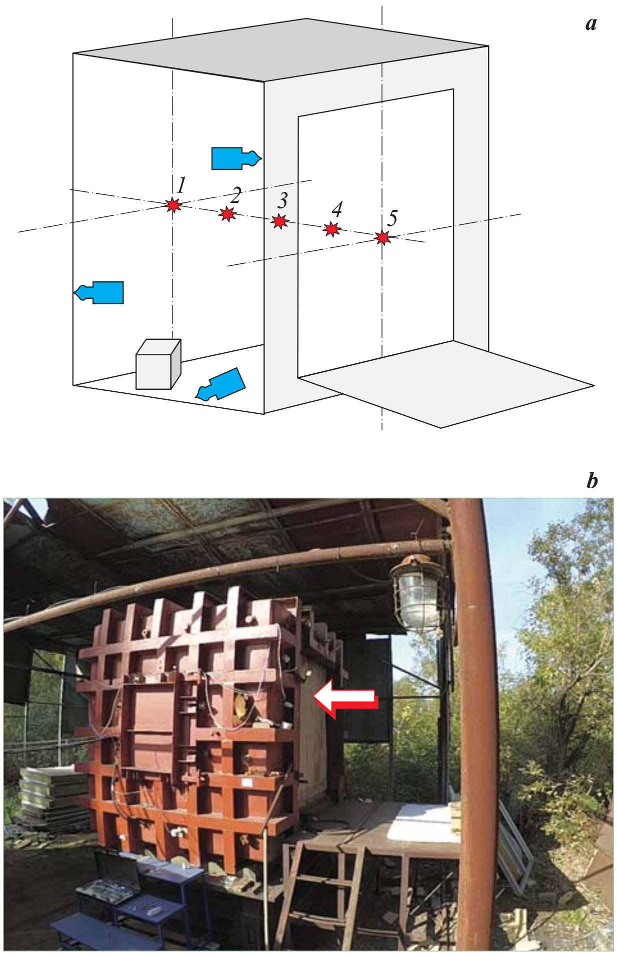

Fig. 1. Diagram of the chamber (*a*) and its initial state (*b*): [sensor icon] — pressure sensors; *1–5* — locations of ignition device; the arrow shows the valve location

the ignition device was moved along the chamber axis from the valve to the back wall. According to the design of the experiment, ignition happened in five various points: in the window plane, in the center of the chamber, at the back wall and in the midway from the center.

To provide enclosed nature of the small chamber when preparing the mixture, the relief window were locked with a multi-use valve made of laminated wood with the surface density of 5 kg/m^2. During the explosion, the valve is opened and the gases are releases to the atmosphere. The valve was pressed against the body with two calibrated 1.2 mm wires located in the upper part of the valve and breaking when the pressure in the enclosure rises. The lower part of the valve was similarly pressed with four wires of the same diameter, thus ensuring that the top wires to be broken first and the bottom ones last. Such a sequence of actuation of collapsing elements allowed rather confidently reproducing the first pressure peaks of explosions in the chamber.

Measuring equipment. The pressure measuring system included the following devices: three piezometric pressure transmitters MPX5050GP (at the back wall, as the center of the sidewall and at the front wall near the window); transmitter power supply BP04B-42; ADC LA-20 USB (manufactured by ZAO Rudnev–Shilyayev) and a PC. A standard version of Microsoft Excel 2010 was used for data processing and plotting.

Gas concentration in the volume was determined by measuring its voluminous flow with a household-grade orifice gas meter BK G4T (manufactured by Elster-Gmbh, Germany). The meter is provided with a thermal compensation device to reduce the influence of ambient air temperature, thus ensuring admissible error of measurement throughout the working range: 1.5 % maximum.

However, there is another type of error due to the process of filling the chamber with gas. The thing is, the pressure in the chamber increases, leading to gas-air mixture leaving the chamber through any type of leaks and openings, usually at the joint between the valve and the body. This leakage reduces the real value of gas concentration in the room, the error may reach up to 2.5 %. Thanks to accurate solution of the gas leakage problem, an engineering method for its calculation has been developed [8]. The method allows calculating the gas volume that shall be supplied to the chamber to obtain a required concentration:

$$V_g = V(1 - \sqrt{1 - 2c}),$$

where V_g is the volume of supplied gas, m^3;

V is the chamber volume, m^3;

c is the required concentration.

For instance, for the chamber with the V = 10 m^3 that was employed in the experiments, to attain 5 % concentration, is was necessary to supply 513.3 liter of gas.

Analysis of typical experiment

Fig. 2 shows video capture of an explosion with ignition in Point *2*, where one may see the beginning of valve cracking, its location and the expansive form of the jet exiting the chamber in various moments from the beginning of the explosion. Unfiltered recordings of the three channels of pressure measurement are given in Fig. 3. Three stages of explosion development may be distinguished in the figure. Point 0 means the signaling of the explosion, then, during the first 0.25 sec pressure in the chamber increases to 1500 Pag, then, as a result of valve opening it drops abruptly, forming the first pressure peak. The abrupt drop in pressure causes oscillations that gradually fade. These are Helmholtz oscillations. This statement is grounded in the fact that the oscillation amplitudes and frequencies are virtually the same for all the pressure transmitters, that is, the chamber volume behaves as an integral whole. This effect is well-known and described. Speaking of virtual equality of the amplitudes, we shall nevertheless note that the initial pressure (and oscillation amplitude) at the back wall in Point *A* is somewhat higher than in other points of the chamber. However, this is understandable, as pressure difference with its excesses and deficiencies is the moving force behind the gas flow oscillations when the gas proceeds into the chamber and out of it.

The oscillations fade as the average pressure in the chamber falls to zero, but the explosion process does not end there. As it has been noted by V. A. Gorev et al [10] and C. Regis Bauwens, Sergey B. Dorofeev [18], when the combustion wave approach the corners of the chamber, acoustic oscillations arise (segment BC). There is no doubt that they are acoustic oscillation, as, first, their frequency is much higher than the Helmholtz frequency, and second, despite the same frequency of the oscillation in various points of the chamber, its amplitudes differ (but are of the same order of magnitude). The acoustic oscillations fade with afterburning of the mixture in the chamber, thus ending the explosion process. The same frequency of oscillations (registered by transmitters in various locations of the chamber) is the evidence of an integral oscillatory process inside the chamber, which is possible for radial type of oscillations with standing pressure wave nodes at the chamber walls.

Analysis of the experimental results

Fig. 4 shows the results of processing 20 experimental explosions at 4 % by vol. concentration of gas and five locations of the ignition device (see Fig. 1). Weak repeatability of the experiment is notable, despite the same starting conditions used in its preparation. This circumstance support the complicated nature of studying such a phenomenon as acoustic oscillations in explosions. It may be excused by the fact that other re-

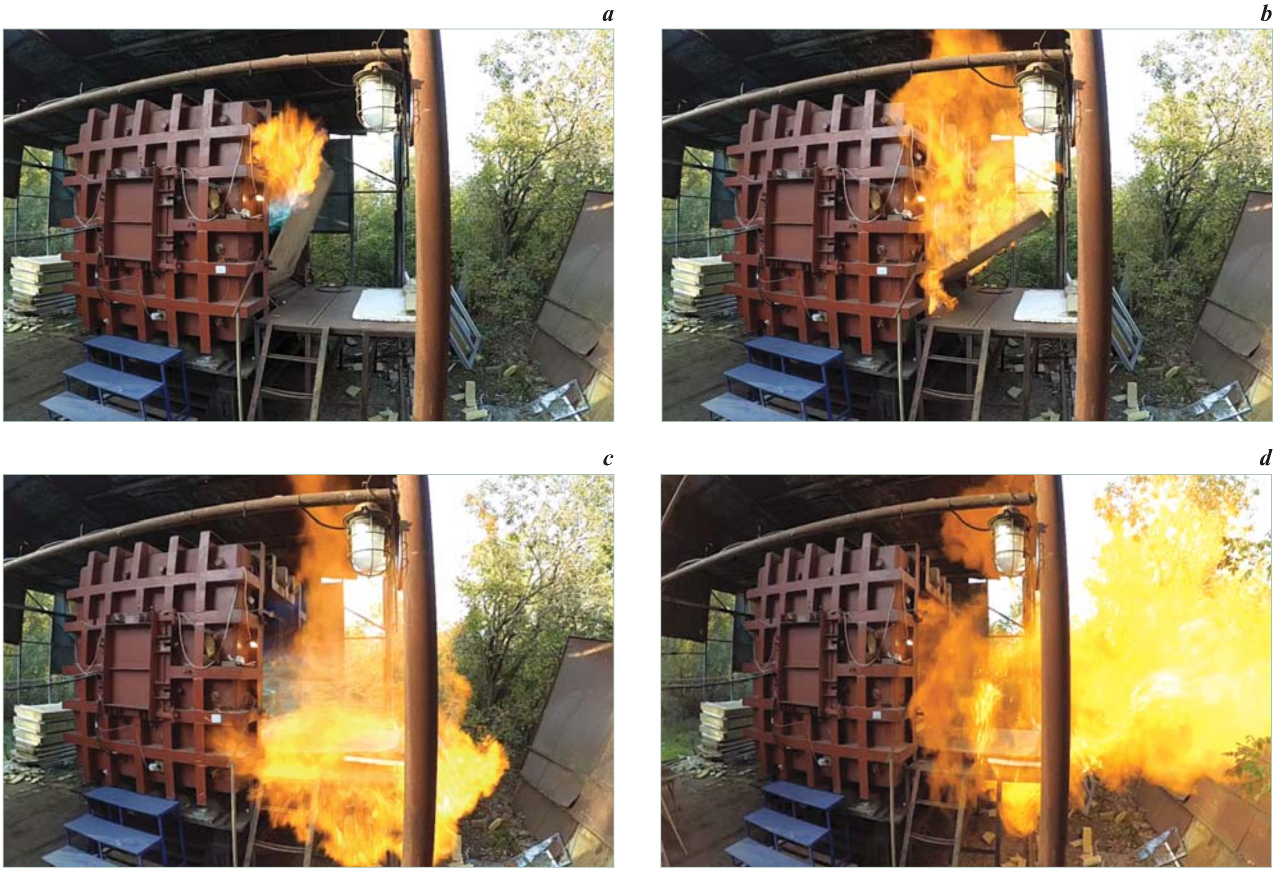

Fig. 2. Still frames from mixture ignition in Point *2* at various moments from the beginning of the explosion: *a* — 0.12 sec; *b* — 0.20 sec; *c* — 0.30 sec; *d* — 0.70 sec

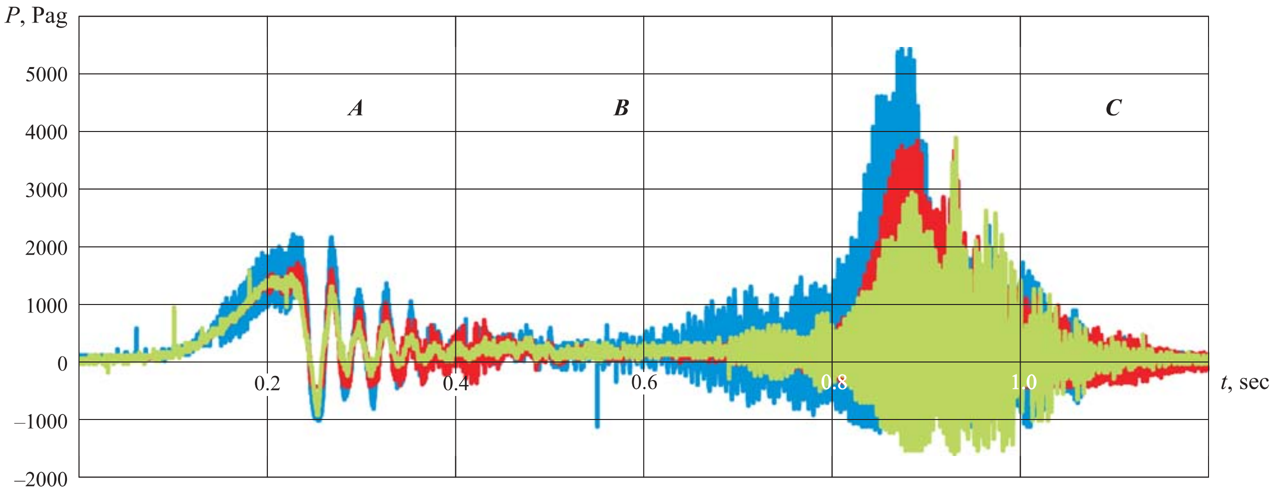

Fig. 3. Pressure evolution in the chamber when igniting the gas in Point *2*: —— — pressure at the back wall; —— — pressure at the side wall; —— — pressure at the front wall

searchers stay away from this issue, so there is nothing to compare this important factor to.

The common oscillatory process and the possibility for a significant growth of their excursion in case of central location of the ignition device (Point *3* in Fig. 1) allow assuming that these oscillations have a radial nature. This hypothesis is in agreement with frequency calculation, if we assume that, on the one hand, the speed of sound in the combustion products is $a = \sqrt{kRT} = \sqrt{1.4 \cdot 290 \cdot 1660} \approx 800$ m/s (where k is Boltzmann's constant, $k = 1.4$; R is the gas constant, for air we may take $R = 290$ J/(kg·K); T is the gas temperature, K), on the other hand, there is a standing wave in the chamber with its quarter-wavelength equal to the half of the chamber's length (radius). In this case, the wavelength L (m) is 4 m, and thus frequency of oscillation $f = L/a = 4/800 = 200$ sec^{-1}, which is virtually the same as in the experimental results. High-speed filming inside

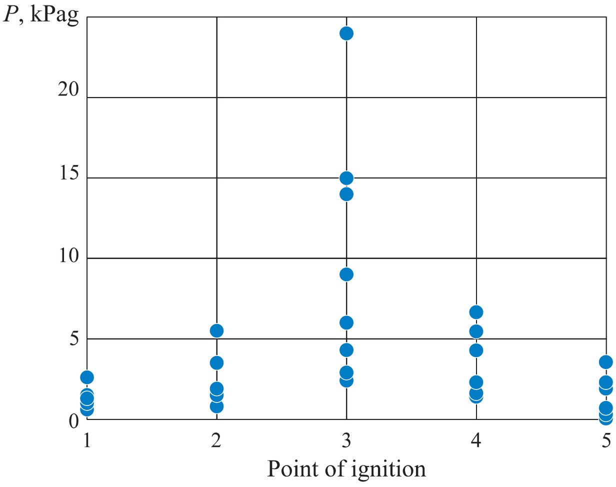

Fig. 4. Maximum excursion of oscillations depending on location of ignition

the camera [10, 11] has shown that the oscillations arise when the combustion wave approaches the walls of the chamber.

In Fig. 4 there is a vivid trend to increased excursion of the oscillations when the ignition device is located closer to the center of the chamber. Despite the wide scatter of the results, especially when igniting in the center of the chamber, one may expect that this variant of ignition results in a possibly most hazardous development of the explosion.

Moving the ignition away from the center of chamber makes the combustion wave asymmetric with respect to the center, thus leading to mismatch of its action upon the oscillatory process of the combustion wave and impossibility to develop a resonance at the radial oscillation frequency. This fact is also supported by results from other researchers [10, 11].

When replacing the light plywood valve with RS with a surface density of 30 kg/m^2 [8], there were no significant Helmholtz oscillations recorded and no symptoms of acoustic oscillations at all (Fig. 5). These results had good repeatability.

It is known, that in closed (without gas relief) chambers the resonant combustion never develops [5]. Speaking of *momentary break of relief section* and *mixture actuation* mentioned in GOST R 12.3.047, first, it is evident that the authors of the standard took Helmholtz oscillations for acoustic ones, and second, influence of actuation onto resonant combustion requires further experimental verification.

There is another interesting effect that was noted when igniting the mixture near the back wall (Fig. 6) and which is well repeatable. It is Helmholtz oscillations of large amplitude represented in Fig. 6 with two peaks against the acoustic oscillations (resonant combustion) of low amplitude. It is possible that it is due to the fact that in this case the most of the gas-air mixture is ejected from the chamber and then immediately explode outside the window (energy of this explosion may cause destruction of glazing in nearby buildings). Explosive pressure during the explosion locks the window section, leading to increased pressure in the chamber and appearance of two pressure peaks with the Helmholtz frequency. Maximum pressure in these peaks is insignificantly higher than the value of the first peak.

In all the experiments where resonant combustion was observed [10, 11], the volume of the room and the area of the window had close values of the dimensionless factor criterion $B = \sqrt{F} / \sqrt[3]{V} = 0{,}53 \div 0{,}60$ (where F is the window area, V *is* the chamber volume). When this criterion is less than 0.5, no resonant combustion was observed [7, 16].

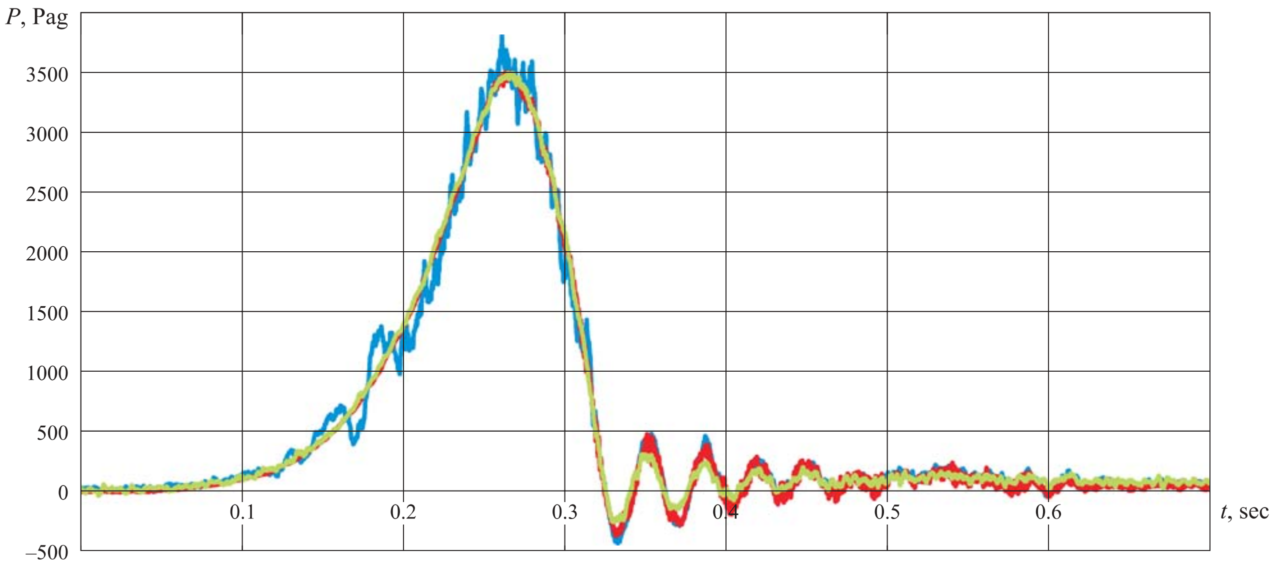

Fig. 5. Pressure evolution when relieving a panel with a weight of 60 kg: —— — pressure at the back wall; —— — pressure at the side wall; —— — pressure at the front wall

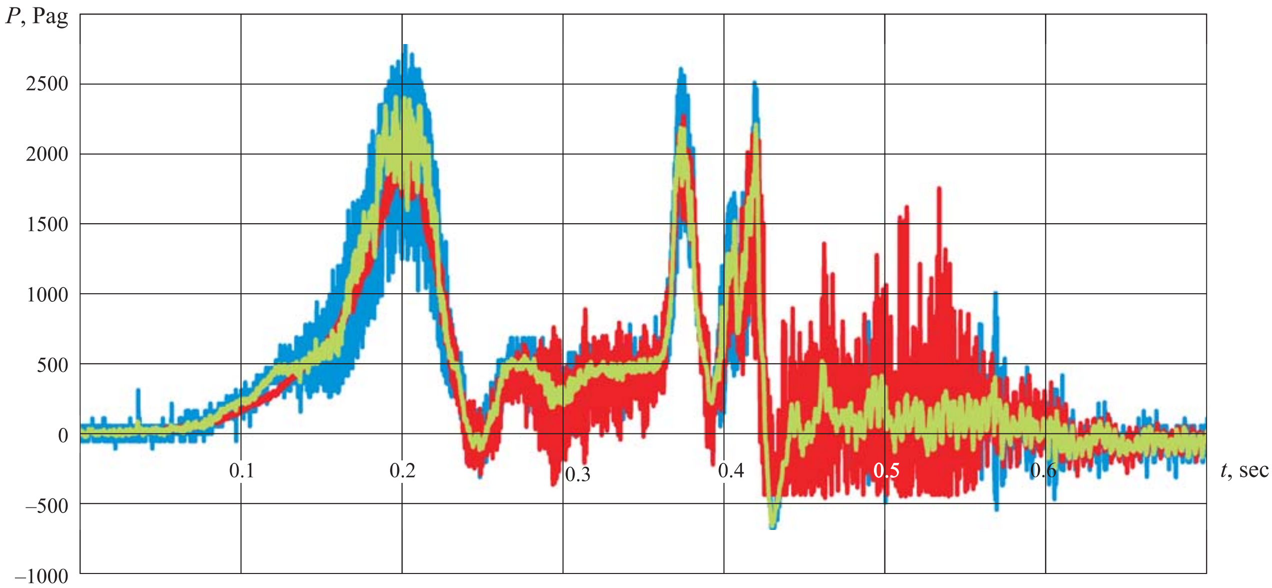

Fig. 6. Pressure evolution for ignition near the back wall of the chamber: — pressure at the back wall; — pressure at the side wall; — pressure at the front wall

Conditions that enable resonant combustion in gas explosion

The experimental data obtained allowed to complement the previously published results pertaining to resonant combustion in explosion. It allowed identifying the conditions that make the resonant combustion possible:

- the size of the chamber is on no importance: this type of combustion was observed for chambers with $V = 1$ m^3 [10], $V = 10$ m^3, and $V = 63$ m^3 [11];
- chamber forms is close to cubic one [10, 11];
- gas-air mixture is close to stoichoimetric one [11];
- the value of criterion B is higher than 0.53;
- the valve (RS) has the surface density lower than 5 kg/m^2;
- ignition of the gas mixture takes place in the center of the chamber.

Deviation from these conditions leads to reduced amplitude of the oscillations in explosion, down to insignificant manifestations of such type of combustion. It is hard to tell, how well these resonant-combustion-enabling conditions may be implemented in an accommodation space.

The Helmholtz oscillations of pressure are irrelevant to the resonant combustion. They arise due to an abrupt drop in pressure when the window is opened, or when the window section is under gas-dynamic lock due to a gas explosion outside the chamber. The amplitude of these oscillations in the first case never exceeds the first pressure peak, while in the second case (explosions outside the chamber) it exceeds the first peak insignificantly.

Conclusions

Resonant combustion in gas explosion increases hazard level. To reduce the hazard, it is necessary to identify the main conditions enabling the resonant combustion. It has been found out, that the oscillations of the highest intensity are observed in chambers that approach cube in theirs form and when the gas-air mixture is ignited in the center of the chamber. Window size, RS weight, quality of the mixture and other factors also influence the amplitude. Radial acoustic oscillations with the frequency of the first mode are characteristic for this type of combustion. The resonant combustion arises when the combustion wave approaches the walls of the chamber. The oscillations are weakened if the ignition source moved away from the center of the chamber, RS weight is increased, window area is reduced or gas concentration is reduced.

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