About the Danger of Vibration Combustion in Gas Explosions in the Room

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Abstract. In recent years, in experimental gas explosions in open volumes, such a phenomenon as vibration combustion has been recorded or, as they sometimes say, flame-acoustic combustion, or simply combustion, but accompanied by acoustic gas oscillations. Generally speaking, this type of combustion was known for a long time in the 19th century, from the time of Higgins and Rijke, and acquired the poetic name “singing flame”. However, at the onset of gas turbine and rocket engines, this phenomenon manifested itself in their combustion chambers and was designated as a whip, as it resulted in structural damage. But the vibration combustion is known not only for the destructive force, but also for the intensification of fuel combustion process in high-duty furnaces.

1. Introduction

More recently, this phenomenon was associated only with stationary or quasi-stationary combustion, but not with such a short-term process as an explosion, which “life” cycle sometimes is a fraction of a second. Now it is difficult to identify who was the first to show that it manifests itself in explosions, but the most well-known are the research results carried out by Gorev V. A and et. al [1] in Russia and a group of US researchers Bauwens C. R. and et. al. [2, 3, 4]. They have shown that in explosions not only a large amplitude of oscillations is present, but the average pressure in the chamber also increases, if compare it with combustion without vibration [5].

But, of course, the question appears, whether such a combustion takes place in real gas explosions in the premises or not. Answer: It is not certain, but this does not mean that it does not exist. Moreover, if take into account that the geometry of experimental chambers with capacity of 1, 10 and 63 м³, in which acoustic oscillations were recorded, and in some rooms, for example, kitchens, are close to each other, so it can be expected with a high degree of confidence that this may be the case. For obvious reasons, there was nobody to record it.

In this regard, it is logical to raise the question of how dangerous vibration combustion is in gas explosions and whether it is worthwhile to deal with it.
2. Methods

2.1. On the hazardous factors in the vibration explosion

Upon reading carefully the materials of studies conducted by American colleagues, one gets the impression that they consider the presence of pressure oscillations, accompanied by an increase in its average value as characteristic of vibration combustion. They focus on the average pressure, considering it the most important process indicator. However, when viewed from the perspective of safety, then we can only partly agree with our colleagues. On the one hand, of course, an increase in the average pressure in explosion is an increase of risk of room collapse. But, on the other hand, a danger is not only there considering the experience of rocket and jet engines development. The vibration combustion in their combustion chambers cannot lead to the average pressure rise, because the average pressure in these units is a function of the fuel supply system performance and flow rate through the nozzle, which means that the average pressure in engines cannot be changed during vibration combustion. But the engine is destroyed. Consequently, the oscillatory component of vibration combustion also has a destructive force. And such factor as oscillations and, especially, their amplitude, is no less important than the average pressure during vibration combustion.

2.2. Review of regulatory documents

Well-known basic explosion safety standards GOST R 12.3.047-2012 (Russia), BS EN 14994: 2007 (EU) and NFPA 68 (USA), on means of mitigating the risks of possible gas explosions in such premises practically do not cover this phenomenon. Only in the Russian standard it is mentioned about the possible influence of vibration combustion on the gas explosion spread, and even then in very general terms. This phenomenon is associated with the relief rate of the Blast Relief Structure (hereinafter: BRS): “…instantaneous” opening of relief section increases the probability of vibration combustion inside the vessel. Amplitude in the acoustic wave of vibration combustion can reach ± 0.1 MPa. Agitation of mix, for example by fan, in the course of an explosion, leads to a decrease in the amplitude of pressure oscillations …".

It should be pointed out that the pressure value mentioned in the quotation is more than one order higher than the standards for permissible pressure in the room (5 kPa), and even then only for those that fall into fire and explosion safety category A or B. The document fails to mention about the other factors, in addition to “instantaneous opening” and “agitation of mix” that affect the vibration combustion. However, this statement casts doubt on the effectiveness of explosion safety measures not designed for this dangerous type of combustion.

With regard to realities, this means, on the one hand, that the danger of premises destruction and risks estimated by human and financial losses are much higher than those indicated in standards, and, on the other hand, the study of vibration combustion in gas explosions should be considered as a problem.

2.3. On the prediction capability for vibration combustion

It is almost impossible to investigate the vibration combustion on the basis of mathematical models developed in “pre-computer” time and based on the description of “feedback mechanisms” [5–7]. This is primarily due to the fact that the vibrations that develop during vibration combustion are non-linear, and the mechanisms that excite them are also non-linear. In short, these are self-oscillations. And the equations that describe the process in those years could be only linear or, in extreme case, have small nonlinearities. And not only for that reason. The fact is that the acoustic oscillations that occur during vibration combustion are a process with parameters distributed in space and can be described by gas dynamics equations, which can be solved only by numerical methods, which is practically impossible
without computer due to a significant amount of computations. Currently, high hopes are laid on numerical CFD (Computational Fluid Dynamics), methods, but these hopes have not yet been justified, because up to now they have failed to describe these self-oscillations. [4, 8, 9].

In this regard, we would like to mention one of our article [10-14], which directly answers the question of modeling the development and damping of oscillations in explosion in the cylindrical chamber with a hole in the side surface. Note that no oscillating circuits and "feedbacks" were laid in the system of equations describing the process of explosion development: they emerged themselves as a result of the evolution of solution [15-20]. Unfortunately, in volumes that are geometrically similar to chambers in which significant acoustic oscillations were recorded, it has not yet been possible to describe self-oscillations.

Understandably, the costly and inefficient experimental method is available for the vibration combustion study. The danger of gas explosion in case of vibration combustion is assessed in this paper. The danger is assessed by comparing two characteristic features of the process: average pressure and amplitudes of oscillations and pressure without vibration combustion. The experimental procedure is based on a change in the gas concentration from explosion modes in which there will be no vibration at all, to the modes where the vibration appears.

2.4. Test stand of the experiment

The experiment was conducted in the base of the Institute of Integrated Safety in Construction at NRU MSUCE using a cubic explosion chamber with a volume of 10 m³, corresponding to GOST R 56289-2014, and with a discharge window of 2 m² (Fig. 1). Propane was fed into the chamber to obtain a mixture with air of a given concentration. A fan for mixture stirring and an ignition unit, located in the center of the chamber, are installed inside the chamber.

In order to ensure that the small chamber volume is closed during the mixture preparation, the discharge chamber window was closed with a reusable valve made of multilayer plywood with superficial density of 5 kg/m². In explosion valve was opened, and gases were discharged into the atmosphere. The valve was pressed to the body by two calibrated wires of 1.2 mm in diameter, placed in the upper part of the valve that disintegrate with pressure rise in the vessel.

2.5. Measuring instruments of the experiment

The pressure measuring system included the following instruments: three piezometric pressure sensors MPX5050GP (on the back wall, on the side wall in the center and on the front wall next to the window); sensor power supply unit BP04B-42; analog-to-digital converter LA-20 USB (manufactured by Rudnev-Shilyaev CJSC) and a personal computer. When processing the database and graph plotting, the standard Excel 2016 program was used. Simultaneously, video was recorded from the window side, synchronized with the recording on PC.
Gas concentration in the vessel was determined by measuring its volumetric flow rate using a domestic gas meter BK G4T of diaphragm type (manufacturer - "Elster-Gmbh", Germany). The meter is equipped with a temperature compensation device to reduce the influence of outdoor temperature, which provides an acceptable measurement error in the entire operating range - no more than 1.5%.

However, there is another error which is generated in the course of gas chamber filling. The fact is that pressure builds up in the chamber at the same time, resulting in the outflow of gas-air mixture from it through all kinds of leaks. This leakage reduces the actual gas concentration in the tank; the error can be up to 2.5%. Due to the accurate gas leakage problem solving, it was possible to develop an engineering calculation method [15]. The method enables to calculate the required gas volume that must be fed into the chamber in order to obtain a given concentration:

\[ V_g = V \left( 1 - \sqrt{1 - 2c} \right) \]

where
- \( V_g \) – feed gas volume, m\(^3\);
- \( V \) – chamber volume, m\(^3\);
- \( c \) – expected concentration.

For example, for a chamber with a capacity of \( V = 10 \) m\(^3\) used in the experiment, it is necessary to send 513.3 l of gas to achieve a concentration of 5 %.
3. Results and discussion

3.1. Analysis of a typical experiment

Figure 3 shows a typical pressure record of the explosion process over the three recording channels; sensor readings were not filtered. The first thing to be taken into account is the practical repetition of the explosion behavior obtained by colleagues from the United States. [2]. Three explosion stages can be identified according to the records. Point "0" means the signal "ignition". At the first stage (OA interval), the pressure increases with the window closed. It is apparent that the pressure rise is accompanied by the development of oscillations at the back wall, which dying away at point A, that is, at the moment of complete opening of the window. These oscillations have acoustic in nature, because the other two sensors practically do not register them: pressure and speed of oscillations are unevenly distributed over the chamber space.

After point A, the pressure in the chamber begins to decrease sharply. This leads to oscillations of different frequency and type, which then gradually dying away in the AB interval. The basis for the statement that these oscillations have a Helmholtz frequency is the practical coincidence of oscillation amplitudes and frequencies between all pressure sensors in this area, that is, the chamber volume acts as a whole. This effect is well known and described. With regard to the practical coincidence of amplitudes, however, it should be noted that the initial pressure at the back wall in point A and, accordingly, the amplitude of oscillations in this place is somewhat greater than in other points of the chamber. But this is clear, because the pressure drop either in excess or in deficit is the driving force for gas flows both from the chamber and into the chamber. Oscillations decay together with the decrease in average pressure in the chamber to almost zero. It would seem that everything should decay in the chamber. But no. As noted by the authors of publications Gorev V.A. and etc. [1] – earlier, and C. Regis Bauwens, Sergey B. Dorofeev [8] - a while later, - when a gas-air mixture burns out, vibration combustion occurs in the corners, accompanied by significant pressure oscillations (Fig. 2). This was the case in our experiment, the acoustic oscillations are set up.

3.2. The dependence of amplitude of oscillations on the concentration of propane

In search of the most dangerous option for the explosion build-up, the dependence of amplitude of oscillations on the concentration of propane in the air was analyzed. Experiments (Figure 3) showed that, near the minimum concentration limit for ignition, vibration combustion can hardly be taken into account.

![Figure 2](image-url)

**Figure 2.** Explosion at $c\approx3,1\%$ of propane. The pressure build-up in the chamber in gas ignition in the position. Blue color - pressure at the back wall; red color - on the side wall; green - on the front wall
With an increase in the concentration of propane to 3.4%, the amplitude of oscillations increases abruptly, after which a further increase in the concentration practically does not affect the amplitude of oscillations.

It was observed that changes in gas concentration build-up two main options of oscillations. One of them is exponential at \( c = 4.9 \% \) (Fig. 4 on the left); all 3 sensors detect synchronous, in-phase oscillations with equal amplitudes. On the one hand, this is similar to the Helmholtz oscillations, but the oscillation frequency of 120 Hz is too high for this. The option of growing acoustic oscillations of radial type with pressure node in the center of chamber and beam on walls must be accepted.

![Figure 3](image1.png)

**Figure 3.** The dependence of amplitude of oscillations on the concentration of propane in the air

![Figure 4](image2.png)

**Figure 4.** Two options for oscillations build-up on the left - at a concentration of 4.9%, on the right - at 5.2%

### 4. Conclusions

Let us take into account that dangerous in explosion, in terms of structural failure, is not only the pressure at which the window opens, but also vibration combustion, accompanied by a significant amplitude of oscillations. The assessment of vibration combustion hazard can be carried out by the oscillation strength, estimated according to the accepted definitions. At developed vibration combustion, the sound intensity reaches 3 kW/m², which is much higher than the pain threshold of perception. At the same time, an oscillating force with an amplitude of 5000 N per square meter acts on the chamber walls.
In rooms that have regular (close to square) shapes in a plan view, the high-intensity acoustic oscillations can develop in gas explosions. This occurs at gas concentrations close to stoichiometric and higher. The amplitude of pressure oscillations can reach 6 kPa, which represents a significant destructive factor.

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