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EXPERIMENTAL RESEARCH INTO THE INFLUENCE OF TWO-SPARK IGNITION ON THE DEFLAGRATION TO DETONATION TRANSITION PROCESS IN A DETONATION TUBE

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Досліджувалася проблема ініціювання детонації в пульсуючих детонаційних двигунах. Напрямок вирішення даної проблеми обрано застосування детонаційних труб з багатоосередковим запалюванням. Як джерела запалювання використані два іскрових розряди, які запалювалися синхронно. Іскрові розряди запалювалися на відстані, за якої забезпечувалася інтенсивна газодинамічна взаємодія між розрядами. Взаємодія полягала в зіткненні ударних хвиль, що генеруються іскровими розрядами. В результаті, в області між іскровими проміжками забезпечувалося зростання температури газу за рахунок зіткнення ударних хвиль, що зустрічно рухаються.

Дослідження впливу двоіскрового запалювання на час і довжину ділянки переходу горіння в детонацію в детонаційній трубі проведено шляхом порівняння параметрів переходу в випадках одноіскрового і двоіскрового запалювання за інших рівнозначних умов досліджень. Дослідження проводилися на детонаційній трубі довжиною 2,3 м і внутрішнім діаметром 22 мм. Свічки запалювання розташовувалися в торцевій частині труби. Використовувалася стехіометрична суміш пропану з киснем, що на 50 % розбавлена азотом за початковим тиску в суміші, що дорівнює 50 кПа. Для реєстрації часу розповсюдження фронту реакції і вимірювання швидкості процесу труба оснащувалася 22-ма іонізаційними датчиками. Відстань між джерелами запалювання дорівнювало 6 мм. Довжина розрядного проміжку в кожному джерелі запалювання становила 2,5 мм. Джерела запалювання у вигляді свічок запалювання підключалися до високовольтних блоків із повною енергією розряду 3,3 Дж.

За результатами досліджень виявлено скорочення відстані переходу горіння в детонацію в 1.6...2 рази і часу переходу з 3,9 мс до 1,2 мс в разі переходу від одноіскрового до двоіскрового запалювання.

Отримані результати можуть бути використані під час проектування систем запалювання в пульсуючих детонаційних двигунах

Ключові слова: детонаційна труба, багатоосередкове запалювання, перехід горіння в детонацію, іскрове запалювання

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1. Introduction

Further improvement in internal combustion engines, primarily aircraft jet engines, is associated with the tran-

sition from a subsonic speed of combustion (deflagration) to the supersonic speed of combustion (detonation) [1]. Increasing the fuel combustion rate makes it possible to increase specific power of such engines by increasing the

amount of fuel combusted per unit volume of the engine's combustion chamber. Multiple reduction in a combustion time leads to a decrease in heat losses in the engine by reducing the time for heat exchange between the products of combustion and the walls of the combustion chamber. In addition, in jet engines the detonation combustion ensures the most efficient conversion of energy from fuel combustion into the kinetic energy of a gas flow by the multi-fold increase in pressure in the combustion chamber as a result of the detonation combustion. Together, this makes it possible to significantly increase efficiency of detonation engines.

Detonation engines are designed by major international companies and research centers [2]. In particular, the rotary and pulse detonation engines are developed by the Scientific research laboratory (NRL) of the USA Navy, by corporations Pratt & Whitney (United States) and General Electric (United States). The first successful flight test of a pulse detonation engine was held in 2008. However, so far only the prototypes of such engines have been designed. Although the high efficiency of detonation engines was experimentally confirmed, construction of industrial samples is limited by the presence of a series of unresolved issues [3]. One of such tasks in pulse detonation engines is the initiation of detonation at low consumption of electrical energy and at high frequency of detonation initiation [4].

The work's relevance is predetermined by the need to address the issue on the energy-efficient initiation of detonation, which necessitates studying the process of detonation initiation.

2. Literature review and problem statement

Periodic initiation of detonation in combustible gas mixtures is implemented by powerful spark discharges or by using a detonation tube. If a spark discharge is used for the direct initiation of detonation, then the discharge is implemented such that the fast local heating of gas with a discharge current is achieved [5, 6].

Despite the simplicity of the method for direct initiation of detonation via a spark discharge, it is used only at experimental installations to determine the critical energy of detonation initiation [7]. The main limitation in applying such initiation in pulse detonation engines is linked to the high consumption of energy required to initiate detonation. For example, the total consumption of electric energy on spark initiation in a hydrogen-air mixture, which is sensitive to detonation, at atmospheric pressure exceeds 200 Joules, and in a kerosene-air several kilojoules [8]. Such consumptions are typically proportional to the energy of combustion, released per cycle in the pulsed detonation engines. Therefore, alternative methods for detonation initiation are being developed.

A detonation tube is also used to initiate the detonation [9, 10]. The detonation tube resolves the issue on reducing the consumption of electrical energy to initiate detonation. However, the frequency of detonation initiation in a detonation tube is limited by the time and length of the section where deflagration to detonation transition occurs. These parameters grow particularly in case a mixture of fuel and oxygen is replaced with a mixture with air. Therefore, there are studies aimed at reducing the section and time of deflagration to detonation transition. Such a reduction is achieved by combustion intensification due to the turbuliza-

tion of a gas flow, for example, by using a Schelkin spiral [11]. Focusing and reflection of shock waves are also applied [12]. To activate chemical reactions in a combustible mixture, the combustible mixture is compressed in advance [13] and the corona discharge is applied [14]. Special spark discharges are used to reduce the time of deflagration to detonation transition [15]. Therefore, solving the task on initiating the detonation is considered through the use of specialized spark discharges.

In order to shorten the length and time of deflagration to detonation transition, paper [14] proposed detonation initiation by the running ignition pulse. The study was conducted in a detonation tube with an inner diameter of 51 mm and a length of 1.5 m. The authors used a propane-air mixture and the propane-air mixture enriched with oxygen at a pressure of 0.1 MPa and a temperature of 292 297 K. They applied ignition sources of different types: pre-chamber ignition, spark ignition with a coaxial discharger and a length of the spark interval of 1.5 mm, as well as the spark ignition with an interval length of 2.5 mm. Ignition sources were installed along the tube with a 100 mm step, their quantity was 10 pcs. Each ignition source was connected to the individual high-voltage unit. Each unit included a capacitor of 100 μ F, powered to voltage in the range from 1,500 to 2,500 V. The ignition sources triggering was in sync with the propagation of a compression wave along a detonation tube. Owing to such initiation of detonation, the authors achieved a deflagration to detonation transition at a section of the tube with a length of 0.6 0.7 m. The drawback of this method is the high consumption of electrical energy to initiate detonation, which amount to 3 kJ.

Work [16] studied the impact of multifocal ignition of a combustible mixture on detonation initiation. The study was conducted in a cylindrical chamber with a diameter of 200 mm. The authors used oxyacetylene and hydrogen-oxygen mixtures. A synchronous multifocal ignition was enabled by flame jets coming from the orifices distributed in space. The jets of flame were formed due to spark ignition in the pre-chamber hosting lots of holes. A given study has showed the possibility to intensify the deflagration to detonation transition through the spatial ignition of the mixture. It was also noted that multifocal ignition can be achieved by using multiple spark discharges. However, in this case there is a problem related to the synchronization of discharges.

Article [17] investigated the issue on improving energy efficiency of sources that initiate detonation. The author devised a series of recommendations for addressing the problem of initiation. Among other recommendations, he proposed distributing the sources of ignition in space, as well as making use of the effect of a shock wave intensity amplification when focusing and reflecting it. However, no technical solutions that could implement these recommendations were given in [17].

Thus, the issue that remains to be explored is the influence of multifocal spark ignition with the effect of a shock wave intensity amplification at its reflection on the process of deflagration to detonation transition in a detonation tube.

3. The aim and objectives of the study

The aim of this work is to study experimentally the influence of a dual spark ignition on the time and length of the deflagration to detonation transition in a detonation tube.

This would make it possible to implement an energy efficient system of detonation initiation for pulsed detonation engines.

To accomplish the aim, the following tasks have been set:

- to develop and experimentally explore the discharge characteristics for the system of dual spark ignition;
- to substantiate the conditions for undertaking a research and to explore experimentally the influence of dual spark ignition on the time and distance of the deflagration to detonation transition in a detonation tube.

4. Design and discharge characteristics of the system for dual spark ignition

The designed ignition system employed two spark dischargers. Similar to known systems of multifocal ignition, spark discharges were ignited simultaneously. However, in contrast to known systems, discharge intervals were at a distance L (Fig. 1), which ensured the intensive gas-dynamic interaction between spark discharges. Such an interaction is due to collisions between shock waves generated by the spark discharges. As a result, the domain between spark intervals experiences an increase in gas temperature in the region of collisions between the oncoming shock waves. It also creates the conditions for the large-scale turbulization as a result of gas fluxes flowing over the discharge electrodes.

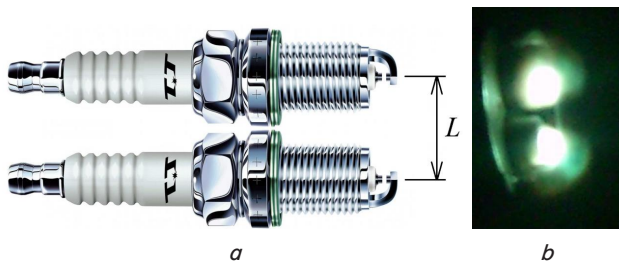


Fig. 1. Ignition system: *a* – schematic of mutual arrangement of ignition sources; *b* – view of spark discharges that ignite synchronously

Distance between the ignition sources equaled $L=6$ mm. Length of the discharge interval in each source of ignition was 2.5 mm. Ignition sources in the form of spark plugs were connected to high-voltage units. We used ignition sources without built-in electric resistance. The source of discharge energy in a high-voltage unit was a capacitor. The total capacity of a battery of capacitors for two ignition sources was $C=1.65$ μ F. The initial voltage of the capacitor charge was $U_{C0}=2,000$ V. The total discharge energy was $Q_{it}=3.3$ J. A simultaneous start of the spark breakdown employed an auxiliary spark discharge.

It is known [18] that energy released over 1 μ s from the onset of a spark discharge mostly determines the intensity of a shock wave. In approximately 1 μ s the density of gas in a spark channel decreases sharply, which drastically reduces the effectiveness of rise in the gas pressure due to its joule heating by a discharge current. Hence the requirement to reduce the duration of the input of energy to the spark channel to 1 μ s. For the RLC-circuit, used in the current study, such a requirement, given a fixed discharge capacity, is met by a decrease in the inductance of a discharge circuit. To reduce this inductance, we used capacitors with an internal inductance of 15 nH. We also arranged wiring in the form of

closely spaced buses to reduce the inductance of a discharge circuit [19]. The total inductance of the discharge circuit was determined based on the results from the discharge oscillography.

Examining the inductance of a discharge circuit typically employs measurement of a discharge current. However, the inclusion of a current sensor requires changing the arrangement of connecting wires, which causes a change in the inductance of a discharge loop. Therefore, we measured voltage based on the discharge capacity that does not require changing the discharge loop. Results from the oscillography of a condenser voltage during a discharge are shown in Fig. 2. Measurement was carried out using the voltage probe made by company TEKTRONIX (United States) of P6015A type that has a 1:1,000 dividing factor. The discharge was enabled in a detonation tube filled with air at a pressure of 50 kPa. A given pressure corresponded to the pressure of gas at which detonation was initiated in the subsequent experiments.

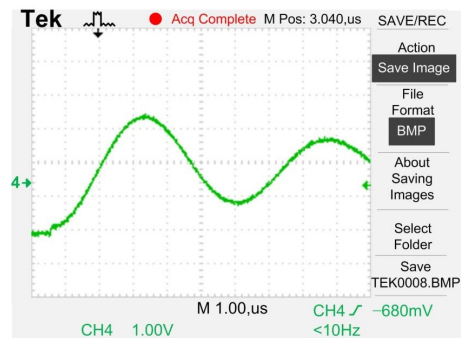


Fig. 2. Measured voltage at the capacitor during a discharge: voltage sensitivity – 1 kV/div; time base – 1 μ s/div

The resulting dependence of voltage at discharge capacity on time was used to calculate the equivalent inductance and active resistance of the discharge circuit. To this end, we built estimated dependences of voltage on time at known capacitance of the condenser and voltage of its charge while the values for inductance and resistance varied. As a result, using a brute-force method, we determined values for the inductance and resistance at which an acceptable approximation of the experimental curve was achieved. It was established that the equivalent inductance of the discharge chain is $L_c=450\pm 20$ nH, and the active resistance of the discharge chain equals $R_c=100\pm 10$ mOhm. The estimated dependences of voltage and current over a discharge gap take the form shown in Fig. 3. The estimated current amplitude reaches 3,400 A.

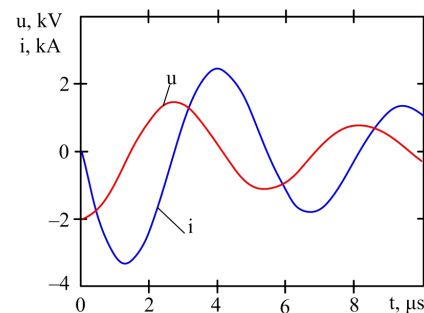


Fig. 3. Estimated dependences of voltage and current at ignition sources

The results obtained show that the duration of the first quarter of the period of capacitor discharge to a source of ignition is almost equal to $1 \mu\text{s}$. This testifies to the acceptable inductance of the discharge circuit, since the first half-period of the discharge produces more than 50 % of the energy input into a spark.

5. Experimental setup to study the process of deflagration to detonation transition

The study was conducted at the experimental bench of the Institute of Heat and Mass Transfer at Belarus NAS. The experimental bench is made using a detonation tube (1) as a base, whose length was 2.3 m, internal diameter of 22 mm (Fig. 4). Spark plugs were arranged at the closed end of the tube.

To register the arrival time of the flame front and to measure the process rate, the tube was equipped with 22 ionization sensors that made it possible to register a conduction current within the front with a spatial resolution of 0.5 mm. Sensors were arranged in one line at a distance of 65 mm from each other, the first of the sensors was at a distance of approximately 775 mm from the ignition point of the mixture. The output signals from the sensors were recorded using oscilloscopes, the waveforms were then processed using a computer. To improve reliability when treating the waveforms, the sensors were divided into 2 measurement lines with 11 sensors in each.

We used a stoichiometric mixture of propane with oxygen, diluted with nitrogen by 50 %. The mixture was prepared in advance, by a manometric method. The prepared mixture was used in 1–2 days when the complete mixing of components was warranted due to the mutual diffusion of gases. The study was carried out at an initial pressure in the mixture equal to $p_0=50 \text{ kPa}$.

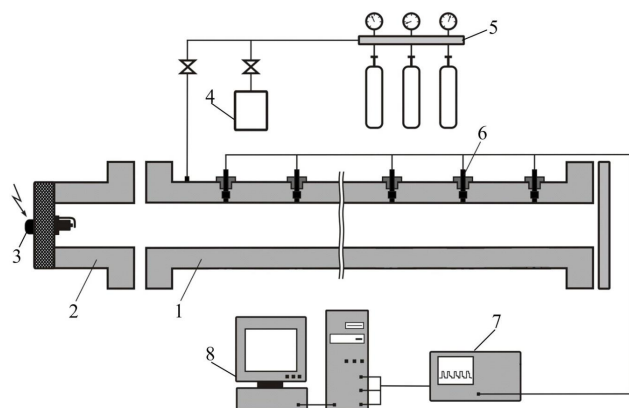


Fig. 4. Schematic of the experimental setup: 1 – detonation tube; 2 – ignition chamber; 3 – sources of ignition; 4 – vacuum pump; 5 – rack with gas cylinders; 6 – ionization sensors; 7 – measuring complex; 8 – PC

We studied the influence of the ignition source on the process of detonation initiation in a detonation tube by comparing the parameters of a deflagration to detonation transition for the single-spark and dual-spark ignition systems. To maintain the boundary conditions for initiation similar when employing different ignition systems, in both cases the same spark plugs were used; only for the case of single-spark ignition the discharge was generated over a single discharge interval.

6. Results of experimental research into detonation initiation

The length and time of deflagration to detonation transition was determined from analyzing the respective signals from ionization sensors, $x-t$ process diagrams and the dynamics in the rate of the deflagration to detonation transition process along the axis of the detonation tube dependent on the point of spark ignition.

Fig. 5 shows the ionization current oscillograms acquired for the case of single-spark ignition.

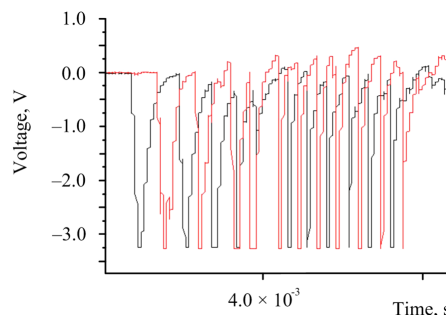


Fig. 5. Ionization current oscillogram for the case of single-spark ignition

The result of signal processing was the determined dependence of the current position of the deflagration or detonation wave front in the tube on time in the form of an $x-t$ diagram of the process of deflagration to detonation transition. The results were then converted into the dynamics of the flame propagation process rate lengthwise the tube.

In the shown $x-t$ diagrams, the results from experiments No. 1, 2 match the conditions for ignition by single-spark discharge, No. 3, 4 – ignition by two spark discharges (Fig. 6).

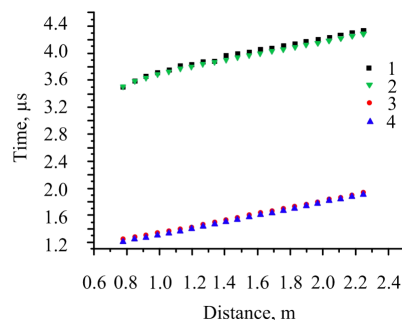


Fig. 6. The $x-t$ diagrams of signals from ionization sensors: No. 1, 2 – ignition by single-spark discharge; No. 3, 4 – ignition by two spark discharges

The diagrams above demonstrate that at single-spark ignition (curves No. 1, 2) the deflagration to detonation transition (DDT) at the section of a tube fitted with ionization sensors. If one uses dual spark ignition (curves No. 3, 4), detonation occurs prior to reaching a first ionization sensor (775 mm from the point of ignition).

Zooming the $x-t$ diagrams for a larger scale (Fig. 7) has helped clarify that the DDT time for the case of single-spark ignition amounted to $t_d=3.9...4 \text{ ms}$. For dual spark ignition, the time of DDT was around 1.2 ms. In other words, we have obtained a decrease in the transition time by more than 3 times for the case of the transition from single-spark to dual-spark ignition.

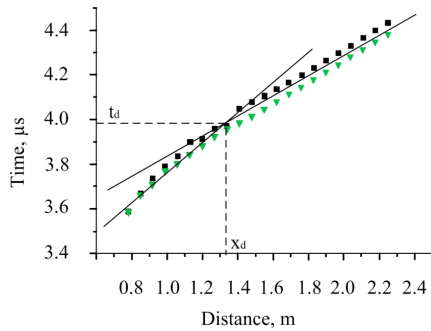


Fig. 7. The $x-t$ diagrams of the deflagration to detonation transition process for single-spark ignition: x_d – distance; t_d – deflagration to detonation transition time

Thus, the use of dual spark ignition under conditions of our experiments resulted in the reduced time of DDT, larger than by 3 times.

Fig. 8 shows the dynamics of change in rate along the axis of the tube. Lengthwise the tube, from 0.8 to 1.3 m, the acceleration of the flame front is observed. At the section from 1.3 to 1.7 m, one observes the rate of a detonation wave exceeding the Chapman-Jouguet speed for a given mixture. Next, there is a shift to the stationary detonation wave.

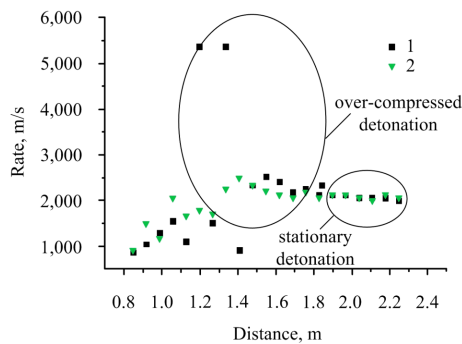


Fig. 8. Dynamics of rate change along the axis of the tube during the process of deflagration to detonation transition for single-spark ignition

The shown dynamics of rate change for the case of dual spark ignition (Fig. 9) demonstrate the presence of the over-compressed detonation at the initial section of the measured section, that is, at a distance less than 775 mm.

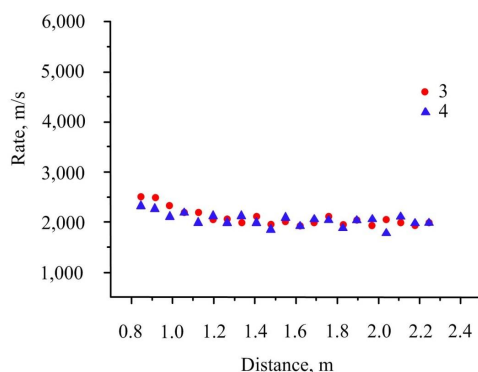


Fig. 9. Dynamics of rate change along the axis of the tube during the process of deflagration to detonation transition for dual spark ignition

The above helped establish that under conditions of our experiments the DDT length for the case of single-spark ignition was $x_d=1.3...1.4$ m, and when ignited by two spark discharges – $x_d=0.7...0.8$ m. Thus, we have obtained a decrease in the DDT length by 1.6...2 times.

7. Discussion of results of studying the influence of dual spark ignition on the process of deflagration to detonation transition

The multifocal ignition method can be further advanced by creating the conditions for interaction between shock waves generated by the spark sources of ignition. Practical implementation of the proposed method is ensured by a special mutual arrangement of discharge electrodes as shown in Fig. 1.

Comparing the times and rates of deflagration to detonation transition (Fig. 6, 8, 9) for single-spark to dual spark ignition reflect the benefits of dual spark ignition with interacting discharges. That solves the task on energy efficient initiation of detonation.

Certain limitations should be noted for the current study. Thus, the use of ionization sensors can only measure the flame propagation process along a tube. Therefore, based on the results from our research, we determined the flame speed, the length, and the time of a deflagration to detonation transition. To reveal the mechanism of influence of ignition on a given transition process, it is required to apply measurement techniques that would make it possible to explore changing the shape of the flame front in a tube. For example, such methods include Schlieren-photography. Thus, the results obtained have demonstrated the appropriateness of undertaking the next phase of research.

A given research field requires further advancement. One needs to determine the optimal distance between spark discharges at which the most effective interaction between shock waves generated in the discharges is achieved. There is a need to identify the parameters for a spark discharge that would minimize total energy consumption to initiate detonation. Limitations of the current study are related to the use of propane-air mixtures. Implementation of pulse engines requires the use of aviation fuel as fuel. The shortcomings of the current work relate to the limited matrix of the experiment, which does not make it possible to define the optimal parameters for a system of dual spark ignition.

8. Conclusions

1. We have designed a dual spark ignition system whose special feature is providing the conditions for interaction between shock waves generated by spark discharges. Based on the results from experimental study, it was revealed that the duration of the first quarter of the capacitor discharge period to a source of ignition in the devised ignition system is almost equal to $1 \mu s$. This ensures energy efficient generation of the initiating shock wave in a spark discharge.

2. The results from our experimental study into the influence of dual spark ignition on the deflagration to

detonation transition process have established a decrease in the DDT length by 1.6...2 times and the DDT time by more than 3 times in comparison with single-spark ignition. Based on the obtained results, we re-

commend using the dual spark ignition with a reciprocal arrangement of discharge intervals at a distance of 6 mm in pulsating detonation devices instead of single-spark ignition.

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