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Initiation of Detonation in Flows of Fuel–Air Mixtures

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Regimes of self-ignition of the fuel mixture obtained by controlled separate injection of hydrogen and air into a plane-radial vortex chamber with a rapid (0.2 msec) transition to detonation have been realized for the first time. Self-ignition occurs in the stoichiometric region with a slightly higher (up to 6–30%) content of hydrogen and, normally, in a subsonic flow. The energy of guaranteed detonation initiation is determined for combustors of different geometries and different ratios of fuel components by using a thermal pulse produced by blasting a wire by electric current. Detonation initiation is ensured by using energy of 0.1 J. It is found that the main contribution of energy into the flow of the mixture occurs at the stage of evaporation (ionization) of copper of the blasted wire. The continuous spin detonation regime is found to decay as the exit cross section of the combustor is reduced. In the regime of combustion, both detonation and conventional turbulent combustion, the pressure at the periphery of the plane-radial vortex chamber is lower and the pressure at the edge of the exit orifice is higher than that in the case of exhaustion of cold fuel components.

Key words: self-ignition, blasted wire, detonation initiation, fuel, vortex combustor, continuous spin detonation.

INTRODUCTION

The interest in initiation of detonation in fuel–air mixtures is caused by the problem of detonation combustion of the fuel in combustors of various engines and powerplants. This problem was encountered to be particularly urgent in the development of pulsed air-breathing engines [1, 2]. It turned out that detonation initiation in a flow of a fuel–air mixture by a low-power source (spark) requires the use of long tubes exceeding the pre-detonation section length or the use of settling chambers (pre-detonators) where the detonation wave is generated in the fuel–oxygen mixture and then is driven to the fuel–air mixture. In the first case, greater dimensions are needed, and the frequency of the working process is lower. In the second case, it is necessary to use an additional and dangerous oxidizer (oxygen). Detonators cannot be used for direct initiation of detonation during continuous cyclic operation of the chamber for numerous reasons, including the strength of the structures. Estimates are available, which show that the energy of initiation of a quiescent or moving fuel–air mixture by an electric spark can be reduced by means of repeated initiation [13]. In experiments with the use of obstacles in the tube cross section [4], Shchelkin's spiral and a special structure of detonation tubes, or repeated initiation of the burning mixture by an electric spark, the pre-detonation distance of the fuel–air mixture and the total energy of initiation could be substantially reduced [5, 6]. The objective of the present work was to ensure spontaneous initiation of detonation of hydrogen–air mixtures in a small-scale chamber and to determine the minimum initiation energy that guarantees detonation development. The problem is solved by forming a special flow in the combustor. The source of energy was the thermal pulse generated by blasting the wire by supplying electric current.

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Experiments in a plane-radial vortex chamber ($d_1 \gg H$, where d_1 is the chamber diameter and H is the distance between the plane walls) with all fuel–oxygen mixtures, including kerosene–oxygen mixtures, showed that spontaneous detonation was developed within the first milliseconds after injection of the fuel components into the chamber [7]. This phenomenon was examined experimentally and numerically in [8–10]. It was shown that detonation can also be initiated if oxygen is diluted by air. With decreasing fraction of oxygen in the mixture, the self-ignition delay increased. If the oxygen–air mixture was prepared immediately before the experiment (there was no mixing of oxygen and air at the molecular level), the self-ignition delay was smaller. If oxygen was injected after air injection, self-ignition occurred if the oxygen amount added to air was 2.5% (by volume). Only one case of hydrogen self-ignition in a pure air flow was observed. This phenomenon cannot be explained by the influence of the mean temperature because its increase reached as the chamber was filled by the mixture was within 410 K. There were also some cases of self-ignition under conditions of a steady flow with the temperature lower than room temperature. At the same time, it is known [11] that the air flow temperature should be sustained approximately at 930 K for several milliseconds for hydrogen to ignite in the air flow (under shock-tube conditions). Thus, the mechanism of self-ignition could not be elucidated.

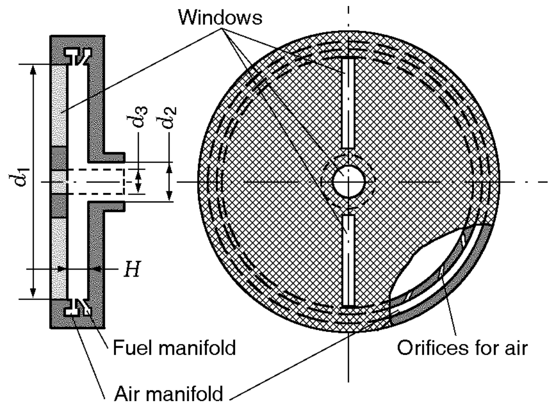

Fig. 1. Combustor.

1. EXPERIMENTAL COMBUSTOR, SETUP, AND MEASUREMENT TECHNIQUE

1.1. Experimental Combustor

A sketch of the experimental combustor is shown in Fig. 1. The combustor was a semi-closed volume bounded by walls: one cylindrical wall with a diameter $d_1 = 204$ mm and two plane-radial walls separated by the distance $H = 15$, 10, and 5 mm. Combustion products escaped through an orifice with a cylindrical extension 40 mm long. The orifice diameter was varied in different experiments: $d_2 = 100$, 70, 50, and 40 mm. In some tests, the chamber was additionally equipped with cylindrical inserts: inserts with a diameter $d_3 = 90$, 40, and 30 mm were placed into orifices with a diameter $d_2 = 100$, 70, and 50 mm, respectively. A series of tests was performed with a completely closed orifice d_2, the plug surface being flush-mounted with the surface of the combustor wall. Thus, a completely closed plane-radial cavity simulating the chamber of an internal combustion engine was formed. An input for combustion initiation was located on the opposite flat wall at a distance of 70 mm from the center. There were two radial windows and one circular window made of Plexiglas for photographing in the same wall. In some experiments, the electrodes were mounted directly in the Plexiglas window at the same distance from the center to register the moment of wire blasting. The process of detonation initiation was recorded onto the film of a photorecorder, which moved perpendicular to the larger side of the windows. The velocity of luminous objects along the combustor windows was determined by the sweep method as $v_r = k \tan \alpha_v v_p$, where $k = 20.2$ is the zoom-out coefficient, α_v is the angle between the trajectory and the horizontal line, and $v_p = 100$ m/sec is the velocity of the film. Spin detonation waves were recorded with partial compensation of velocity through one window and with complete decompensation through the other window, because the waves moved in the opposite directions. The velocity of the spin waves was determined by the method described in [12].

The system of air injection had a receiver with a volume of 3.2 liters from which air first entered an annular manifold with a cross-sectional area of 4 cm^2 and then the chamber through a number of orifices uniformly distributed along the cylindrical wall of the chamber and directed at an angle of 30° to the tangent of the cylindrical surface (see Fig. 1). In several experiments, air did not pass through the manifold and entered the combustor through two orifices of large cross section, which were directed along the tangent to the cylindrical surface. The fuel (hydrogen) was injected from a receiver with a volume of 1.6 liters into an annular manifold with a cross-sectional area of 1 cm^2. The fuel exhausted into the combustor through a number of orifices uniformly distributed along the combustor cir-

TABLE 1

Parameters of Injectors

Injector	Orifice cross section, mm	Number of orifices	Total cross-sectional area of orifices, mm^2
F1	0.3×0.5	180	27
F2	0.3×0.25	180	13.5
A1	0.5×1.2	300	180
A2	1.0×4.0	50	200
A3	10×10	2	200

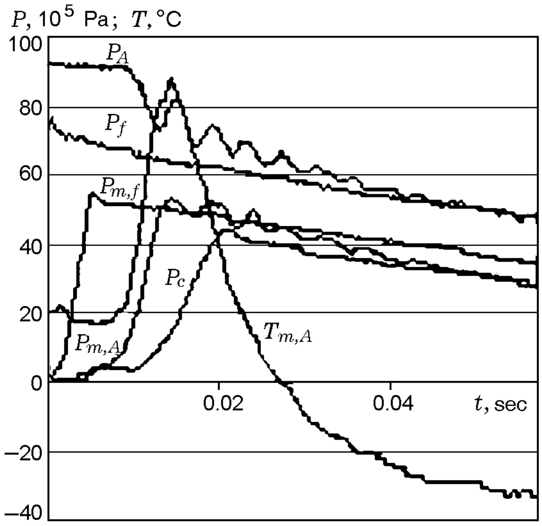

Fig. 2. Typical oscillogram of parameters of the process in an experiment without detonation initiation ($d_2 = 50$ mm and $d_3 = 30$ mm).

cumference and directed at an angle of 45° to the generatrix of the cylindrical surface and at an angle of 45° to the surface of the flat walls in the upstream direction. The parameters of various injectors for air (A) and fuel (F) are listed in Table 1. Various combinations of these injectors were used.

1.2. Measurement of Pressures and Flow Rates of the Gases

The radial distribution of static pressure in the combustor (P_c) was measured by strain-gauge transducers with a resolution of 0.1 msec, which were installed at a distance of 1 cm from each other. The same transducers were used to measure the pressure in the air receiver (P_A) and hydrogen receiver (P_f) and also the pressures in the corresponding manifolds ($P_{m,A}$) and ($P_{m,f}$). The pressures measured in the manifolds were close to stagnation pressures because of the low flow velocities in the manifolds. Typical oscillograms for these parameters are plotted in Fig. 2 (it refers to the regime without initiation). To make the figure more readable, only one curve P_c corresponding to the radius $R_c = 98$ mm (4 mm from the cylindrical wall) is given here.

Injection of air and hydrogen from the receivers was performed through fast-response electromagnetic valves with an opening time of about 1 msec (disregarding the duration of the transitional process in the electromagnetic system). The initial pressures of air and hydrogen in the receivers were varied within $P_{A,0} = (102–23) \cdot 10^5$ Pa and $P_{f,0} = (100–20) \cdot 10^5$ Pa, respectively. If the pressures of the gases in the corresponding manifolds have passed the maximum by the moment of detonation initiation (see Fig. 2), their flow rates were determined from the changes in pressure in the corresponding receiver [13]. As the initiation of the mixture formed in the combustor often occurred with increasing pressures in the air and hydrogen manifolds (immediately after opening of the valves), the flow rates through the corresponding injectors were determined by the known formula $G = \mu\rho v S$. Here μ is the flow-rate coefficient assumed to be 0.8 [13]; ρ and v are the gas density and velocity in orifices with a cross-sectional area S, respectively. To determine the gas density in the manifold ρ_m, it is insufficient to know only the pressure P_m, because exhaustion from the receiver to the manifold is not isentropic in the transitional regime, since a work of compression of the gas entering the manifold is performed [10]. Therefore, the stagnation temperature of the gas in the manifolds (T_m) was also measured with the use of fast-response thermocouples [9]. Based on the measured values of P_m and T_m, the gas density in the manifold could be determined by the equation of state of the gas $RT_m = P_m/\rho_m$, where R is the gas constant. At the beginning of the manifold-filling process, the gas passed through the injectors with a velocity of sound ($P_m/P_c \geqslant 1.86$); therefore, the gas-exhaustion parameters were determined by the formulas $\rho = \rho_* = \rho_m[2/(\gamma + 1)]^{1/(\gamma-1)}$ and $v = c_* = c_m[2/(\gamma + 1)]^{0.5}$, where ρ_* and c_* are the gas density and velocity in the throat of the injector, and γ is the ratio of specific heats of the gas. In the case of subsonic exhaustion of the gas through the injector ($P_m/P_c < 1.86$), the flow rate of the gas was determined from the decrease in pressure in the corresponding receiver. The error in determining the flow rates of the gases escaping from the receivers was within 3%, as was estimated in [13]. In the region of initia-

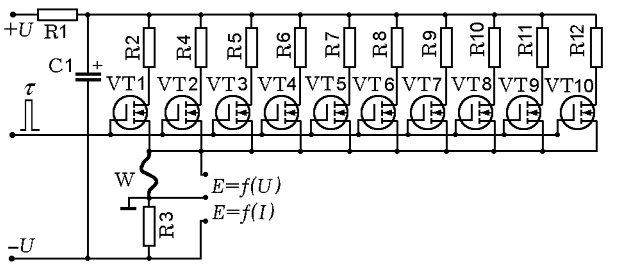

Fig. 3. Electrical circuit of wire blasting.

tion, the flow rates of air and hydrogen varied within $G_A = 3$–0.4 kg/sec and $G_f = 0.065$–0.04 kg/sec, respectively.

1.3. Determination of Initiation Energy

Detonation of the hydrogen-air mixture was initiated by blasting copper wires 2 mm long with a diameter $d_w = 0.07$, 0.1, or 0.13 mm by electric current. The wires were soldered to the electrodes and were flush-mounted with the combustor wall at a distance of 32 mm from the cylindrical surface of the chamber.

The layout of the initiating device is shown in Fig. 3. The discharge capacitor C1 was charged through the charging resistance R1 to a voltage of 30 V. At a time prescribed by the control scheme, the transistors VT1–VT10 were opened, and the capacitor discharged to blast the wire W. The time of current supply (response time of the transistors) was 0.2 μsec. To restrict the discharge current (to 1300 A), the resistances R2 and R4–R12 were mounted. The discharge time could be restricted by the duration of transistor operation set by the generator of rectangular pulses (pulse time τ).

The current I was measured from a calibrated shunt R3 connected into the electric circuit, and the voltage U was measured directly at the ends of the blasted wire. The total cross-sectional area of all input current-conducting wires was greater than 2 mm^2. To reduce spurious inductance and capacitance of the circuit, the initiation device was located at a minimum possible distance from the electric input into the chamber (it was attached to the chamber itself). The voltage and current signals were recorded by a computer-aided system with a resolution (discretization time) of 0.78 μsec. The released energy E_i was determined by the formula $E_i = \int\limits_0^t IU\,dt$.

Fig. 4. Typical photographic record of self-ignition of a hydrogen–air mixture with a transition to detonation: combination of injectors F1/A1, $d_2 = 40$ mm, $H = 15$ mm, at the moment of initiation, $P_c = 44 \cdot 10^5$ Pa at the point $R_c = 70$ mm; $\phi = 1.1$.

2. DISCUSSION OF TEST RESULTS

In all experiments, hydrogen was injected into the chamber before air injection (see Fig. 2). The ratio of the components in the chamber was permanently changing: from the excess of hydrogen during the increase in pressure in the air manifold to the deficit of hydrogen in a steady process of exhaustion of the gases because the air receiver was emptied faster than the hydrogen receiver. The exhaustion process can be regarded as "steady" only to a certain extent, because the flow rates of the components decreased in this case as well. This decrease in the flow rates, however, proceeded smoothly, without an increase in temperature of the gases in the manifolds. Thus, the mixture formed in the chamber passed through the point of stoichiometry two times: during the transitional process and during the steady process of exhaustion of the components into the combustor.

2.1. Self-Ignition

In the first set of experiments, a targeted search for conditions of self-ignition of the hydrogen–air mixture was performed. First, we fixed the combustor geometry and the injection conditions: $d_2 = 40$ mm, $H = 15$ mm, combination of injectors F1/A1, and initial pressures in the hydrogen and air receivers $P_{f0} = 78 \cdot 10^5$ Pa and $P_{A0} = 93 \cdot 10^5$ Pa, respectively. Self-ignition during the transitional process was observed in each tenth experiment (Fig. 4). Ignition occurred inside the chamber but outside the field of vision of the windows. When approaching the windows, the flame front propagated with a phase velocity of about 605 m/sec along the window. Reflection from the cylindrical wall resulted in formation of a detonation wave moving with a velocity $D = 1850$ m/sec. As was shown by the static pressure gauge mounted at the combustor radius $R_c = 70$ mm, the pressure at this moment was $P_c = 44 \cdot 10^5$ Pa, and the equivalence fuel-to-air ratio was $\phi = 1.1$. It is seen from Fig. 4 that the processes in the exit cross section of the combustor do not have any direct upstream influence on self-ignition of the mixture formed. The level of pressure in the chamber was estimated by using its value at the point $R_c = 70$ mm, where the initiating wire was placed in subsequent experiments. The pressure at this point is a certain intermediate value between the maximum pressure at the combustor periphery and the minimum pressure at the edge of the exit orifice. It should also be noted that a transition of the core flow from quasi-solid rotation to a potential vortex occurred in the vicinity of this point [8, 9]. The values of pressure at other points will be specially indicated if necessary. By chance, ignition origination could be registered opposite the windows close to the chamber periphery, at a distance of 2/3 of the chamber radius, in air enriched by oxygen [10]. As these mixtures are highly active, detonation initiation occurred in the first accelerating wave before its reflection from the cylindrical wall of the chamber.

For a further search for self-ignition conditions, we performed tests with a fuel injector F2 whose cross-sectional area was half that of the injector F1. In this case, air injection was performed through the injector A2, which had greater orifices than the injector A1 but the same total cross section. The combustor geometry, the injection system, and the initial pressures of the components in the receivers were unchanged. The injector F2 made it possible to ensure a smaller decrease in pressure in the hydrogen manifold during hydrogen injection into the combustor. In this test series, each second experiment involved self-ignition. Self-ignition was observed in the range of pressures $P_c = (20\text{–}44) \cdot 10^5$ Pa with a moderate excess of the fuel $\phi = 1.06\text{–}1.27$. A rather large scatter in pressures in the chamber and an almost constant value of ϕ suggest that the mixture in the chamber of this geometry and with this system of injection is initiated at the moment when mixing provides an approximately stoichiometric ratio of the components. Self-ignition was observed both during the increase in air pressure in the manifold (with increasing flow rate of air) and during the steady regime after the air pressure in the manifold had passed through the maximum. Self-ignition was normally preceded by subsonic exhaustion of the components into the chamber. A lower probability of self-ignition in the case of using the injector F1 can be attributed to more rapid development of the situation where the ratio of the components approached the stoichiometric value. As the exit diameter of the combustor was increased to $d_2 \geqslant 50$ mm, no self-ignition was observed. If pure oxygen was used, self-ignition also occurred in the combustor with $d_2 = 100$ mm at the early stage of supersonic exhaustion of oxygen into the chamber [10].

Yet, if an insert with a diameter $d_3 = 30$ mm was placed into the orifice $d_2 = 50$ mm and the cross-sectional area of the combustor was retained at the value for $d_2 = 40$ mm ($S_2 = 12.56$ cm^2), self-ignition of the mixture was observed again approximately with the same frequency of occurrence. Self-ignition was persistent for pressures in the chamber of $\approx 27 \cdot 10^5$ Pa both in the transitional and in the steady regimes in the stoichiometric region. Mounting an insert with $d_3 = 90$ mm into the exit orifice of the chamber with $d_2 = 100$ mm ($S_2 = 14.9$ cm^2) and reduction of the distance between the flat walls to $H = 5$ mm in the combustor with $d_2 = 70$ mm ($S_2 = 11$ cm^2, which is already determined by the area of the annular layer at the exit orifice rather than the cross-sectional area of the orifice) ensured a cross-sectional area close to that in the case with $d_2 = 40$ mm, but did not lead to self-ignition in this statement. Apparently, the flow structure in the latter case was different and did not allow self-ignition. No self-ignition was observed in a closed combustor (with a plug in the orifice d_2) either.

Of interest was the case where the injector A3 with two tangential inputs into the combustor directly from the pipelines was used. The injector F2, the geometric sizes $d_2 = 40$ mm, $H = 15$ mm, and the initial pressures in the receivers remained unchanged. In this case, a flow-type combustor was modeled. Self-ignition was also observed here in the steady flow regime as the values $\phi = 1.06$ and $P_c = 32 \cdot 10^5$ Pa were reached. It seems strange that mixing sufficient for self-ignition occurs even in air jets of such a large diameter.

Thus, self-ignition of a hydrogen-air mixture in this vortex chamber requires pressures higher than $20 \cdot 10^5$ Pa, fuel-to-air ratios close to the stoichiometric value, and the cross-sectional area of the exit section of ≈ 12.5 cm^2. In addition, the flow structure in the combustor has to remain unchanged, which is the main condition for ignition [10]. Other combinations of geometric parameters of plane-radial vortex chambers with self-ignition are also possible.

2.2. Initiation

In the case of forced initiation, an arbitrary time of wire blasting was set. This made it possible to find the minimum energy that guaranteed ignition both in the stoichiometric region and for other ratios of the components, pressures in the combustor, and combustor geometries.

Preliminary testing of blasted copper wires of different diameters and of length $l_w = 1.5$, 2, and 3 mm in air (outside the combustor) showed that the energy spent on wire blasting is almost independent of the capacitor voltage U. With increasing voltage, it was only the wire-blasting time that decreased, while the blasting energy E_i remained almost constant. Therefore, the value of E_i can be varied by changing the wire diameter d_w, the wire length l_w, and the current-pulse duration. It should be mentioned that the values of U, I, and E_i also depend on the technological process of experiment preparation: quality of soldering the wire to the electrode, initial integrity of the wire, its length and diameter, and quality of contact between the conducting wires and electrodes, because the electric resistance of the contact is commensurable with the resistance of the wire.

The tests were performed as follows. For each combustor geometry, a set of tests without forced initiation of the mixture was performed. If self-ignition occurred, the number of tests was increased. If there was no self-ignition, an attempt was made to initiate the process by a wire with $d_w = 0.07$ mm. If the energy of wire blasting was insufficient for the mixture to ignite, a wire with a greater diameter was used: $d_w = 0.1$ or 0.13 mm. In some cases, the initiation energy was controlled by the duration of opening of the transistors in the blasting circuit.

Let us first consider the test results in the chamber with the following geometry: $d_2 = 40$ mm, $H = 15$ mm, and combination of injectors F2/A2. Figure 5 shows the typical oscillograms of current and voltage for detonation initiated in the mixture flow by a wire 0.07 mm in diameter. The current-pulse duration is restricted by the integrity of the wire and the plasma column, whereas the voltage-pulse duration is limited by the transistor-opening time. After the current circuit is broken, the voltage on the electrodes is set equal to the voltage on the capacitor (30 V). During the first 20 μsec, the current increases to the maximum value, and the voltage increases only by 2 V. Apparently, wire heating and melting occur during this time, and the melt is heated to the boiling point. This time is twice longer if the wire 0.1 mm in diameter is used and thrice longer if the wire diameter is 0.13 mm. The mass of the wire increases approximately by the same factor, which indirectly supports this assumption. For thicker wires, the energy contribution into the mixture flow increases owing to both longer duration of the first stage of heating (until wire failure) and higher values of U and I in their integer and plasma states.

An analysis of the current and voltage oscillograms shows that the duration of the capacitor discharge through the plasma is approximately identical for all wires (if the transistor-opening time is not artificially reduced) and reaches 40–50 μsec. In tests performed outside the combustor, in quiescent air, where the plasma conductor was affected only by electrodynamic forces of the current circuit and by internal pressure of the plasma column, the discharge duration in the plasma was two to three times longer. This means that the effect of gas-dynamic forces on the discharge region is also significant in a flow-type combustor; these forces entrain the plasma downstream, shortening and equalizing the discharge duration in all wires during their failure. With allowance for the specific features of the experimental technology noted above, the discharge energy for wires with $d_w = 0.07$, 0.1, and 0.13 mm was $E_i = 0.1$–0.2, 0.3–0.6, and 0.6–1.2 J, respectively.

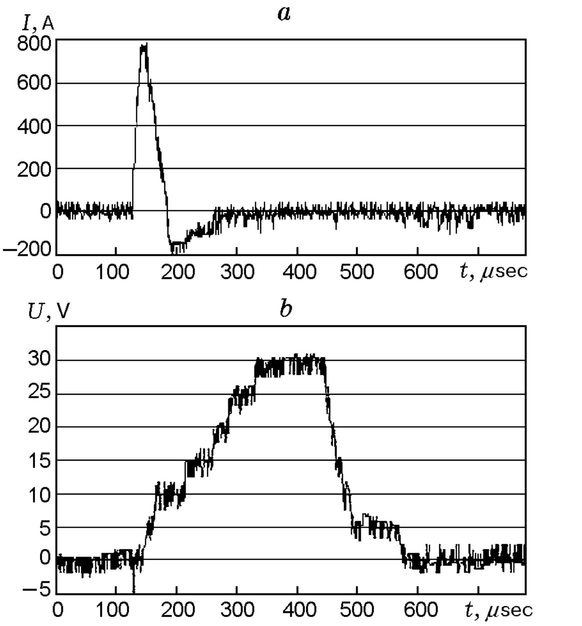

Fig. 5. Typical oscillograms of current (a) and voltage (b) in the course of wire blasting ($E_i = 0.1$ J).

The energy of the electric discharge through the wire with a diameter $d_w = 0.07$ mm calculated from the oscillograms in Fig. 5 was $E_i = 0.1$ J. This energy was sufficient for guaranteed initiation of detonation in mixtures in the stoichiometric region. It is much smaller than the energy of direct initiation of detonation in a quiescent hydrogen–air mixture, which is 4.6–6.6 kJ for a pressure of 10^5 Pa in a three-dimensional region and can be reduced to 1.4–1.75 J for a pressure of $30 \cdot 10^5$ Pa and recalculation to a two-dimensional region [14]. Its magnitude is lower than the discharge energy in a car plug (>0.12 J [15]), which initiates the mere turbulent combustion in the chamber of an internal combustion engine. To demonstrate this statement, a set of experiments on ignition initiation was performed with a spark plug in a standard statement from a source of d.c.

current of 12 V through a standard ignition coil. Detonation was initiated even for less favorable conditions in the combustor: $d_2 = 70$ mm and $H = 5$ mm.

Let us estimate the energy contributions to wire failure (E_f) at the stages of wire heating (E_h), melting ($E_{\rm melt}$), heating of the melted wire to the boiling point ($E_{m,b}$), and boiling (E_b):

$$E_f = E_h + E_{\rm melt} + E_{m,b} + E_b = cm(T_{\rm melt} - T_0) + mh + c_{m,b}m(T_b - T_{\rm melt}) + mL_b.$$

Here $c = 0.385$ kJ/(kg · K) and $c_{m,b} = 0.49$ kJ/(kg · K) are the specific heats of solid and melted copper, $m = \pi d_w^2 l_w \rho_{\rm Cu}/4$ is the wire mass, $T_{\rm melt} = 1356$ K and $T_b = 2890$ K are the melting and boiling points of copper, $T_0 = 293$ K is the initial temperature, $h = 205$ kJ/kg and $L_b = 4.8 \cdot 10^3$ kJ/kg are the specific heats of melting and boiling of copper, and $\rho_{\rm Cu} = 8930$ kg/m^3 is the copper density. For the wire of length $l_w = 2$ mm and diameter $d_w = 0.07$ mm, the corresponding energies are $E_h = 0.016$ J, $E_{\rm melt} = 0.006$ J, $E_{m,b} = 0.02$ J, and $E_b = 0.134$ J, and the total energy is $E_f = 0.176$ J. For wires with $d_w = 0.1$ and 0.13 mm, the total energy increases in proportion to the wire mass by a factor of 2 and 3, respectively. This estimate shows that the wire with $d_w = 0.07$ mm evaporated only partly, and drops of the melted metal entered the mixture flow in addition to ionized atoms of copper.

Let us estimate the energy contribution of the wire to the flow prior to wire failure. The amount of heat transferred to the flow by a cylindrical wire, with heat transfer to electrodes being neglected, is determined by the relation $\Delta q_w = \alpha S_w \Delta T \Delta t$, where $\alpha = {\rm Nu}\lambda/d_w$ is the heat-transfer coefficient, ${\rm Nu} = 0.18{\rm Re}^{0.62}{\rm Pr}^{0.33}$ is the Nusselt number in the flow around a cylindrical body aligned perpendicular to the flow [16], ${\rm Re} = vd_w/\nu$ is the Reynolds number, v is the flow velocity, ν is the kinematic viscosity of air, Pr is the Prandtl number, $S_w = \pi d_w l_w$ is the area of the wire surface, ΔT is the difference in wire and gas-flow temperatures in the vicinity of the wire, Δt is the time of wire heating, and λ is the thermal conductivity of air. Assuming that $d_w = 0.1$ mm, $\lambda = 2.6 \cdot 10^{-2}$ J/(m · sec · K), $\nu = 15.1 \cdot 10^{-6}$ m^2/sec, $v = 200$ m/sec [9], $\Delta T = 1.5 \cdot 10^3$ K (mean temperature of the beginning of heating prior to copper evaporation), $\Delta t = 40 \cdot 10^{-6}$ sec, and ${\rm Pr} \approx 1$, we obtain $\Delta q_w = 0.15 \cdot 10^{-3}$ J. Emission of the wire can be estimated by the known formula $\Delta q_r = \sigma\varepsilon S_w T_w^4 \Delta t$, where $\sigma = 5.67 \cdot 10^{-12}$ J/(cm^2 · sec · K^4), ε is the integral emission coefficient equal to unity for the blackbody surface, and T_w is the wire surface temperature. Even in the melted state of copper, the loss of heat of the wire for heat transfer to the gas and emission is smaller than the heat loss due to convective cooling by two orders of magnitude. Comparing the values of Δq_w and Δq_r with E_f, we can conclude that the heat transfer toward the mixture flow prior to wire failure can be neglected. Thus, energy addition into the flow mainly occurs during the capacitor discharge over copper in the ionized state. The electron conductivity of copper in the course of its evaporation is replaced by the ion conductivity with increasing voltage on the electrodes. During the time interval when the current flows over copper in the plasma state (40 μsec), the mixture moving with a velocity $v \approx 200$ m/sec will cover a distance $l_v \approx 12$ mm. This narrow region in the wake flow behind the wire can be considered as a heat-release zone, as the gas phase and metal drops several microns in size under the above-described conditions in the combustor reach the velocity of the ambient flow almost immediately [8].

Figure 6 shows the photographic record obtained in an experiment with the electrodes mounted directly in the window of the combustor with $d_2 = 70$ mm and $H = 10$ mm. The electrodes close part of the window and are seen as a narrow dark band in the record. In this case, the central circular window is closed. It is seen that the flame spot is entrained by the gas flow whose velocity at this time is approximately 200 m/sec. All windows become illuminated in 0.2 msec almost simultaneously: in the vicinity of the electrodes in the upper window and close to the exit orifice of the combustor in the lower window. The phase velocity of the flame front along the windows is ≈550 m/sec. The luminous region in the upper window moves both upstream and downstream. Reflection from the zone of outflow from the combustor immediately generates a stronger detonation wave propagating with a velocity of 1170 m/sec upstream over the flow of the partially burnt gas behind the preceding weak wave. Being reflected from the cylindrical wall, the weak detonation wave in the second window generates a detonation wave moving downstream over the flow of the partially burnt gas with a velocity of 1700 m/sec. In 1 msec after interaction of these waves, which subsequently degenerate into shock waves, with the spots of the products and fresh mixture, stable continuous spin detonation with two transverse detonation waves moving with a velocity $D = 1830$ m/sec with respect to the cylindrical wall of the combustor is established. In the case of forced detonation initiation, the time of its stabilization is longer (0.3 msec). This is fairly logical: the mixture is less prepared than that in the case of self-ignition.

Figure 2 shows that hydrogen with a pressure up to $(2.5–5) \cdot 10^5$ Pa enters the air manifold through the injectors from the combustor if air is injected later than hydrogen. If the beginning of initiation was too early (first milliseconds of air exhaustion), it was possible to

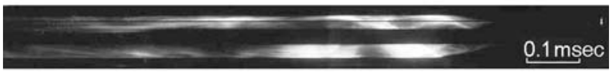

Fig. 6. Typical photographic record of forced initiation of detonation in a hydrogen–air mixture: the central window is closed; combination of injectors F2/A2, $d_2 = 70$ mm, $H = 10$ mm, at the moment of initiation (bright flash at the beginning of the record), $P_c = 17 \cdot 10^5$ Pa at the point $R_c = 70$ mm; $\phi = 1.2$; $E_i = 0.33$ J.

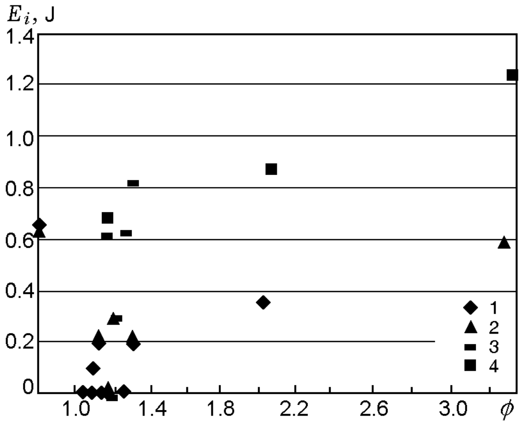

Fig. 7. Initiation energy versus the equivalence ratio in chambers of different geometries: points 1 refer to $d_2 = 40$ mm, points 2 to $d_2 = 50$ mm and $d_3 = 30$ mm, points 3 to $d_2 = 70$ mm, and points 4 to $d_2 = 0$ (closed combustor); combination of injectors F2 and A2; $H = 15$ mm.

initiate detonation by a low energy (0.18 J) at low pressures ($3 \cdot 10^5$ Pa). This event was observed in the combustor with $d_2 = 70$ mm and $H = 5$ mm, though the boundary layers on flat walls almost merged [9]. Apparently, there was premixing of hydrogen and air in the air manifold, and initiation conditions were improved. No self-ignition, however, was observed in the combustor of this geometry.

Figure 7 shows the detonation-initiation energy E_i as a function of the equivalence ratio for the hydrogen–air mixture in combustors of different geometries. Points corresponding to self-ignition ($E_i = 0$) in the range of pressures in the combustor from $20 \cdot 10^5$ to $44 \cdot 10^5$ Pa are also indicated. Strictly speaking, these values of E_i are not the minimum necessary energies of initiation of the mixture because of the scatter in wire-blasting energies, but they guarantee detonation initiation. We confined ourselves to the values of E_i presented because the search for the exact values of the minimum energy of initiation of the mixture would increase the necessary effort by an order of magnitude, which does not seem justified at the current stage of detonation-initiation research.

As it could be expected, the smallest value of E_i is needed for the combustor with $d_2 = 40$ mm and $H = 15$ mm both in the vicinity of the stoichiometric ratio and away from it. For $\phi < 1$, the detonation-initiation energy drastically increases. Enrichment of the mixture by the fuel is more favorable for ignition of the mixture, and self-ignition can occur in the region $\phi = 1.06$–1.28. Reliable initiation of detonation is provided with the energy $E_i = 0.1$ J. A twofold greater amount of the fuel in the mixture ($\phi = 2$) increases the energy of reliable initiation of detonation approximately by a factor of 4. Initiation energies for the combustor with $d_2 = 50$ mm and $H = 15$ mm and with the insert $d_3 = 30$ mm are close to each other. As was noted previously, self-ignition of the fuel mixture in this combustor is also possible. An increase in the cross-sectional area of the combustor exit to $d_2 = 70$ mm ($H = 15$ mm) increases the initiation energy in mixtures with the ratio of the components close to the stoichiometric value by a factor of 4 to 6. A 1.5-fold decrease in the distance between the walls ($H = 10$ mm) halves the difference; for $H = 5$ mm, the difference decreases by a factor of 3 (two lower points in Fig. 7: $E_i = 0.3$ and 0.18 J, respectively). In the combustor with $d_2 = 100$ mm and $H = 15$ mm, the initiation scheme shown in Fig. 3 could not initiate ignition of the mixture. Detonation was excited only in the range of stoichimetry directly from the source of 36 V without restrictions on the current in the wire. Based on the experimental results of [8], the detonation-initiation energy in this case is estimated as 2.5 J. The detonation-initiation energy in a closed combustor (without an exit orifice) is also comparatively high. For stoichiometric mixtures, it is close to the case with $d_2 = 70$ mm and $H = 15$ mm. The case with fuel deficit was not tested in this combustor. The character of the increase in initiation energy with increasing equivalence ratio is similar to the cases considered above.

After ignition and a transitional process, which is accompanied by interaction of detonation and shock waves reflected from the cylindrical wall and lasts approximately 1 msec, either continuous spin detonation or turbulent combustion with transonic rotating and radial waves was developed in the combustor. The structure of spin waves was considered in detail in [7, 17]. As the exit diameter increases, the process is more likely to turn to the spin detonation regime, and vice versa. A process with two waves moving with a velocity $D = 1780$ m/sec with respect to the outer diameter of the combustor was formed in the chamber with $d_2 = 100$ mm and $H = 15$ mm. The spin detonation regime was also obtained in the combustor with $d_2 = 50$ mm and $H = 15$ mm [7], but no detonation regimes were observed in the chamber with $d_2 = 40$ mm and in the closed chamber. Usual turbulent combustion prevailed there. This result agrees with the data of [17] where a similar situation was obtained in a combustor with a diameter of 80 mm and $H = 5$ mm with the use of fuel–oxygen mixtures. The reason is obvious: an increase in pressure in the chamber caused by a smaller outflow of the products rapidly moves the flow of the fuel components from the injectors to the subsonic region and prevents the inflow of the fresh mixture. For this reason, the formation of a detonation-capable layer of the mixture becomes impossible. It cannot be excluded, however, that the influence of the detonation waves on the injection system at high differences in pressure in the injectors with the fuel components being injected into the combustor with the velocity of sound is limited to a narrow high-pressure region behind the wave front. In this case, a detonable layer of the mixture can be formed, and continuous spin detonation can be achieved.

In the case of ignition and development of combustion (either detonation or usual turbulent combustion), the pressure in the chamber became lower at the periphery and higher at the edge of the exit orifice, as compared with exhaustion of cold products. This result supports the previous experiments and calculations by the potential vortex flow model [7]. The reason is that the combustion products have lower density than the initial mixture and generate smaller centrifugal forces. The rotating high-pressure region behind the detonation-wave front is not large: within 10–20% of the period between the waves. In the present work, we managed to measure the pressure along the combustor radius. Figure 8 shows the curves illustrating this phenomenon. To make the figure readable, only two extreme oscillograms out of eight are plotted: at the points $R_c = 98$ mm (at a distance of 4 mm from the cylindrical surface) and $R_c = 40$ mm (at a distance of 5 mm from the edge of the orifice). The oscillograms at intermediate points lie between these two curves. The curves become closer to each other as the detonation decays because of the lower flow rates.

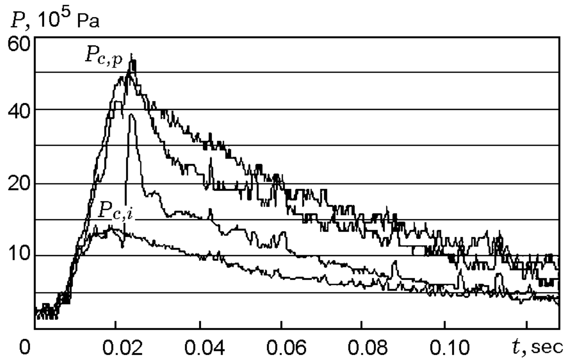

Fig. 8. Time evolution of pressure in the chamber at the periphery ($P_{c,p}$) and at the edge of the exit orifice ($P_{c,i}$) for exhaustion of cold fuel components (extreme curves) and detonation (inner curves) with identical injection conditions: the beginning of detonation is marked by a drastic increase in pressure in the chamber; $d_2 = 70$ mm and $H = 15$ mm.

CONCLUSIONS

1. Regimes of self-ignition of the fuel mixture obtained by controlled separate injection of hydrogen and air into a plane-radial vortex chamber with a rapid (0.2 msec) transition to detonation are realized for the first time. Conditions of self-ignition are found, the main conditions being the flow structure and the ratio of the fuel components. Self-ignition occurs in the stoichiometric region with a slightly higher (up to 6–30%) content of hydrogen and, normally, in a subsonic flow.

2. By measuring the current in the wire and the voltage in the wire during its blasting, the energies of guaranteed initiation of detonation in a hydrogen–air mixture are determined for plane-radial vortex chambers of different geometries and for different ratios of the fuel components. Their minimum values lie in the stoichiometric region with a small excess of hydrogen (correspond to the self-ignition condition). Deviations of the equivalence ratio to either side increase the initiation energy, and this increase is more substantial for lean mixtures with hydrogen deficit.

3. For the setup used, the optimal combustor geometry and injection system are determined, which ensured self-ignition in each second test, and the guaranteed initiation of detonation in the stoichiometric region requires a discharge energy of 0.1 J.

4. The main contribution of energy into the mixture flow is found to occur at the stage of evaporation (ionization) of copper of the blasted wire.

5. For the fuel–air mixture and an unchanged system of injection, the continuous spin detonation regime is found to decay with decreasing exit cross section of the chamber. Usual turbulent combustion is observed in a completely closed chamber. In the regime of combustion (both detonation and usual turbulent combustion), the pressure at the periphery of the plane-radial vortex chamber is lower and the pressure at the edge of the exit orifice is higher than that in the case of exhaustion of cold fuel components.

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