Continuous spin detonation of methane/hydrogen-air mixtures with additional injection of air to combustion products

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Abstract. Results of experimental investigations in a flow-type annular cylindrical combustor with an outer diameter \( d_c = 503 \text{ mm} \) are reported. The influence of air addition to products of continuous spin detonation of a \( \text{CH}_4 + 8\text{H}_2 - \text{air} \) mixture on detonation wave parameters, pressures in the combustor, and specific impulse is studied. The range of existence of continuous spin detonation in terms of the specific flow rate of the mixture through the combustor cross section is extended to \( 1360 \text{ kg/(s}\cdot\text{m}^2) \), whereas the equivalence ratio is reduced to \( \phi_c = 0.4 \). It is shown that addition of air to detonation products up to the level of the air flow rate in the main injection system increases the velocity of continuous spin detonation, pressure in the combustor, and thrust, whereas the specific flow rate of the fuel decreases.

1. Introduction

The results of experimental and theoretical investigations of continuous spin detonation (CSD) based on the scheme proposed by Voitsekhovskii [1] were summarized in [2]. A review of the current status of experimental research of CSD in flow-type annular detonation combustors for some fuel-air mixtures (FAMs) with acetylene, hydrogen, and syngas used as a fuel can be found in [3]. It is known [2] that the diameter of the annular detonation combustor \( d_c \) should be greater than a certain minimum value \( (d_c > d_{c,new}) \) for CSD to occur. Obviously, the minimum critical diameter \( d_{c,new} \) for the most poorly detonable FAM (methane-air) is very large. Therefore, the first experimental data on CSD in the most poorly detonable FAM (methane-air) with addition of hydrogen were obtained in a flow-type annular detonation combustor with a diameter \( d_c = 503 \text{ mm} \) (DK-500) [4]. The goal of the present work is to study the effect of additional injection of air to combustion products in DK-500 on the CSD process, range of its existence, pressure in the detonation combustor, and thrust performance in the \( \text{CH}_4/\text{H}_2\)-air mixture.

2. Experimental

The detonation combustor \( I \) is a coaxial channel with an outer diameter \( d_c = 503 \text{ mm} \), length \( L_c = 680 \text{ mm} \), and annular gap \( \Delta = 18 \text{ mm} \) (Fig. 1). The free cross-sectional area of the channel is \( S_\Delta = \pi(d_c - 2\Delta)\Delta = 274.2 \text{ cm}^2 \). The system for injection of the FAM components into the detonation combustor consists of the following elements: (1) duct for injection of primary air consisting of two receivers 2, valves 3, annular manifold 4, and annular slot 5 of width \( \delta = 3.5 \text{ mm} \) (the free cross-sectional area is \( S_\delta = \pi(d_c - \delta)\delta = 54.9 \text{ cm}^2 \)); (2) duct for injection of secondary air consisting of a receiver 6, valve 7, annular manifolds 8, and annular slot 9 with width \( \delta_1 = 4 \text{ mm} \) (the free cross-sectional area is \( S_{\delta_1} = \pi(d_c - 2\Delta)\delta_1 = 58.7 \text{ cm}^2 \)); (3) duct for injection of the binary fuel \( \text{CH}_4 + 8\text{H}_2 \) consisting of a receiver 10, valve 11, annular manifold 12, and annular injector 13 (600 orifices with the a cross-sectional area
of 0.35×1.45 mm² directed pairwise at angles of 90° and 45° to the combustor axis). The mixture of the fuel components from gas holders 14 and 15 (CH₄ and H₂, respectively) is prepared directly in the receiver 10 with the use of an impeller 16 mounted on the Segner wheel. Primary air and the mixture of combustible gases are injected at the frontal face of the combustor near the outer wall. Secondary air is injected into the combustor at a distance L₄ = 490 mm from the frontal face at an angle of 45° to the flow of combustion products.

![Schematic of the experimental setup](image)

**Figure 1.** Schematic of the experimental setup.

The initial pressures in two air receivers 2 were pᵣ,a₁₀ = pᵣ,a₂₀ ≈ 32×10⁵ Pa, the pressure in the additional air receiver 6 was pᵣ,a₃₀ = 30 or 59×10⁵ Pa, and the pressure in the fuel receiver 10 was pᵣ,ᵣ₁₀ ≈ 74×10⁵ Pa. The flow rates of the components changed in the following ranges: G₄₁ + G₄₂ = 1.28 ± 17.7 kg/s (primary air), G₄₁ = 0.5 ± 18.9 kg/s (secondary air) (the specific flow rates through the annular slot are g₄₁ = (G₄₁+ G₄₂)/S₅₀ = 230 ± 3220 kg/(s·m²)), and CH₄ + 8H₂ - G₅₁ = 0.032 ± 0.83 kg/s (binary fuel). The fuel-to-air equivalence ratio φᵢ at the combustor entrance was 0.65 ± 1.25. The ratio of additional to primary air in the experiments varied as follows: α = G₆₁/G₄₁ + G₄₂ = 0.39 ± 1.03, and the total equivalence ratio was φₑ = φᵢ/(1+ α) = 0.4 ± 0.82. The current flow rates of the FAM at the combustor exit gₑₓₚₓₑₓ = (G₄₁ + G₆₁ + G₅₁ + G₅₁)/S₅₀ were gₑₓₚₓₑₓ = 66 ± 1360 kg/(s·m²). The degree of combustor channel expansion at the entrance was K₅ = S₅₀/S₅₁ = 5.0. The detonation products exhausted into the ambient atmosphere with a pressure pₑ = 10³ Pa.

The process was photographed by a Photron Fastcam SA5 high-speed camera with a rate of 420000 frames per second through longitudinal Plexiglas windows 17 aligned one after the other along the combustor wall (see Fig. 1). The width and length of each window were 20 and 93 mm, respectively, and the distance between the windows was 24 mm. The method of determining the frequency f, number of transverse detonation waves (TDWs) n, and CSD velocity D was similar to that used in [3]. Pressure sensors produced by the Trafag company (Switzerland) with a class of accuracy of 0.5% were applied to measure the pressures in the binary fuel receivers (pᵣ,l), in the receivers of the primary (pᵣ,a₁, pᵣ,a₂) and additional (pᵣ,a₃) air injection, in the fuel manifolds (pᵣ,m₁), and in the manifolds of the primary (pᵣ,m₄₁₂) and additional (pᵣ,m₄₅₃) air injection. The static (pᵣ,a₁, pᵣ,a₂, pᵣ,a₃) and total (pᵣ,a₃₀) pressures in the combustor were also measured. The static pressures (pᵣ,a₁, pᵣ,a₂) were measured at a distance of 15 and 100 mm from the combustor entrance, and the static pressure pᵣ,a₃ and total pressure pᵣ,a₃₀ were measured at the combustor exit.

3. Results of experiments

The two-wave CSD regime and continuous multifront detonation (CMD) with opposing TDWs in a poorly detonable CH₄+ 8H₂ + air mixture in the range of the specific flow rates of primary air through the annular slot g₄₁ = 3220 → 230 kg/(s·m²) at φᵢ = 1.21 → 0.7 with addition of secondary air to combustion products (α = 1.03 → 0.39) were obtained for the first time (Figs. 2.a and 2.b, respectively).

3.1. Photographic records of continuous spin detonation

As g₄₁ = 3220 → 700 kg/(s·m²), φᵢ = 1.21→0.83, and α = 1.03 → 0.794, regimes with two TDWs (n = 2) and rotation frequency f = 2.08→1.64 kHz (D = 1.65 →1.3 km/s) were observed. A fragment of
typical photographic records of the two-wave CSD regime is shown in Fig. 2,a. The TDWs with the front $BC$ with the sideward-emanating tail $CD$ move from left to right. Ahead of these waves, one can see oblique waves $MN$, followed by intense luminescence of detonation products expanding from the TDWs moving in front of them. The size of the front $BC$ is estimated as $h \approx 13$ cm, and the ratio $h/l$ is approximately $1/6$ ($l = 79$ cm is the distance between the TDWs).

![Figure 2. Photographic records (fragments) of CSD and CMD in the $CH_4 + 8H_2 +$ air mixture with additional injection of air: a) CSD: $g_5 = 2560$ kg/(s·m$^2$), $\phi_1 \approx 1.0$, $\alpha \approx 1.0$, $f = 2.08$ kHz, $D = 1.645$ km/s, and $n = 2$; b) CMD: $g_5 = 585$ kg/(s·m$^2$), $\phi_1 \approx 0.8$, $\alpha \approx 0.77$, and $f = 1.4$ kHz.]

With a further change in the parameters $g_5 = 700 \rightarrow 300$ kg/(s·m$^2$), $\phi_1 = 0.83 \rightarrow 0.7$, and $\alpha = 0.794 \rightarrow 0.4$, one can observe the CMD regime with two opposing TDWs and the frequency of wave passage visible through the window $f = 1.4 \rightarrow 1.17$ kHz. A fragment of the photographic records of the CMD regime is shown in Fig. 2,b. Based on these photographic records, it is impossible to estimate the sizes of the fronts of the colliding TDWs because they are not stationary in time and space. The TDW rotation direction was determined by considering the sequence of individual full frames taken by the high-speed camera (slow-motion movie).

3.2. Pressure oscillograms of continuous spin detonation

For the experiment considered above, Fig. 3,a shows the time evolution of the pressure oscillograms in the injection system (receivers and manifolds). The behavior of the pressures in DK-500 and at the combustor exit is illustrated in Fig. 3,b.

![Figure 3. Time evolution of the pressures in the injection system (a) and in the combustor (b): $G_1 = 0.96 \rightarrow 0.033$ kg/s, $G_{ad} = 10 \rightarrow 0.65$ kg/s, $G_{a2} = 9.54 \rightarrow 0.66$ kg/s, $G_{a3} = 18.3 \rightarrow 0.96$ kg/s, $\phi_1 = 1.22 \rightarrow 0.66$, $\phi_2 = 0.6 \rightarrow 0.4$, and $\alpha = 1.03 \rightarrow 0.69$; 1 – initiation, 2 – transition of CSD to CMD, 3 and 4 CSD and CMD parameters corresponding to Fig. 2.]

The process was initiated in a steady flow of hydrogen and air from the second receiver (after the maximum pressures in the corresponding manifolds) after the beginning of additional air exhaustion (its pressure in the manifold only started to increase). Then the valve of the first air receiver was opened. A quasi-steady flow was formed in the combustor only after the pressure in the additional air manifold reached the maximum value. Exhaustion of the mixture of the combustion products and additional air from the combustor was near-critical, and exhaustion of air from the manifold of the main injection system was subcritical and sensitive to changes in combustor conditions. However, the
change in the combustor pressure did not affect the flow rates of the main and additional injection systems, as well as the fuel injection (for air, the flow rates were determined by the minimum free cross sections of the valves). The total pressure was $p_{c30} \approx 12 \cdot 10^5$ Pa at the beginning of the experiment and decreased to $p_{c30} \approx 1.5 \cdot 10^5$ Pa at the end of the experiment, i.e., exhaustion of the products from the combustor became subcritical.

In one of the experiments, additional air was injected later than primary air. The parameters of the main injection system for air and hydrogen were not changed, but the initial pressure in the additional air receiver was halved (down to $p_{a30} = 30 \cdot 10^5$ Pa). Before additional air injection, at $g_a = 3330$ kg/(s·m$^2$), $\phi_1 = 1.28$, and $\alpha = 0$, the CSD regime with two TDWs ($n = 2$) and velocity $D = 1.3$ km/s ($f = 1.64$ kHz) was formed in the combustor. After secondary air injection at $G_{a30} = 8.97$ kg/s for 80 ms, the detonation velocity remained almost unchanged, but then, at $g_a = 2477$ kg/(s·m$^2$), it drastically increased to $D = 1.564$ km/s though the number of waves remained the same ($n = 2$). As a result, the coefficient $\alpha$ became twice smaller at the beginning of the experiment than that in the experiment considered above, but remained almost unchanged at the end of the experiment: $\alpha = 0.53 \rightarrow 0.39$. As $g_a = 3040 \rightarrow 809$ kg/(s·m$^2$), $\phi_1 = 1.25 \rightarrow 0.87$, and $\alpha = 0.53 \rightarrow 0.44$, we also observed regimes with two TDWs ($n = 2$) and rotation frequency $f = 1.99 \rightarrow 1.39$ kHz ($D = 1.57 \rightarrow 1.1$ km/s). With a further decrease in $g_a = 809\rightarrow 230$ kg/(s·m$^2$), $\phi_1 = 0.87 \rightarrow 0.65$, and $\alpha = 0.44 \rightarrow 0.39$, CSD transformed to the CMD regime with $f = 1.33 \rightarrow 1.26$ kHz.

4. Analysis of results

4.1. TDW rotation frequency

The TDW rotation frequency $f$ is shown in Fig. 4 as a function of the specific flow rate of primary air $g_a$, for the examined FAM without additional air injection $G_{a3} = 0$ (points 1) [4] and with additional air injection $G_{a3} > 0$ (points 2 and 3).

![Figure 4. TDW frequency versus the specific flow rate of primary air $g_a$ in DK-500 (CH$_4 + 8$H$_2 +$ air): 1 — $G_{a3} = 0$ [4], 2 — $G_{a3} > 0$, $\alpha = 0.53 \rightarrow 0.39$; 3 — $G_{a3} > 0$, $\alpha = 1.03 \rightarrow 0.4$.](image-url)

It is clearly seen that the TDW rotation frequency and, hence, the CSD velocity with additional air injection is greater than that without additional air injection for identical values of $g_a$. As $\alpha = 0.53 \rightarrow 0.39$ (points 2), there are exceptions in the transitional (in terms of frequency) regions near the specific flow rates $g_a = 760$ and $1500$ kg/(s·m$^2$). As $\alpha = 1.03 \rightarrow 0.4$ (points 3), the difference in the TDW frequencies reaches 30%. No one-wave regimes are observed in the case with additional air injection. However, in the region $g_a \approx 800\pm 50$ kg/(s·m$^2$), the CSD regime transforms to the CMD regime (the TDW frequency drastically decreases), which exists down to $g_a \approx 400$ kg/(s·m$^2$). In the case without additional air injection (points 1), a transition from the two-wave to one-wave CSD regime occurs in the same region. A specific feature of CSD regimes at $G_{a3} > 0$ is the drastic decrease in the frequency $f$. 


without the change in the number of waves in the region \( g_{\delta} \approx 1500 \text{ kg/(s\cdot m}^2) \). The analysis of the photographic records shows that the initial mixture starts to ignite behind the oblique wave \( MN \) (see Fig. 2,a). As a result, the detonation front \( BC \) behind this wave is attenuated, and the TDW velocity decreases.

4.2. Total pressure at the combustor exit

In our experiments, we measured the total pressure of the products \( p_{c30} \) at the combustor exit, which is an important integral characteristic of detonation combustion of fuel-air mixtures. The generalized dependences of \( p_{c30} \) on the specific flow rate of primary air \( g_{\delta} \) in DK-500 for the examined mixture \( \text{CH}_4 + 8\text{H}_2 - \) air with secondary air injection (\( G_{a3} > 0 \)) and without it are shown in Fig. 5. It is seen that the total pressure increases almost linearly with increasing \( g_{\delta} \) in the case of CSD and supercritical exhaustion of the products from the combustor (\( p_{c30} > 1.8 \ p_a \)). At \( G_{a3} > 0 \) (points 2 and 3), the values of \( p_{c30} \) are systematically higher than those at \( G_{a3} = 0 \) (points 1).

For a given degree of DK-500 expansion at the exit (\( K_s = 5 \)) the ratio of the total pressure \( p_{c30} \) to the pressure in the air manifold \( p_{m,a} \) remains almost constant in the examined ranges of the flow rates of the mixture; the value of this ratio at \( G_{a3} = 0 \) is \( p_{c30}/p_{m,a} = 0.45 \pm 0.02 \). Secondary air injection leads to an increase in this ratio, e.g., \( p_{c30}/p_{m,a} = 0.6 \pm 0.03 \) as \( \alpha = 1.03 \rightarrow 0.4 \).

![Figure 5](image)

Figure 5. Total pressure \( p_{c30} \) at the DK-500 exit versus the specific flow rate of primary air \( g_{\delta} \): 1– \( G_{a3} = 0 \), 2– \( G_{a3} > 0 \), \( \alpha = 0.53 \rightarrow 0.39 \); 3– \( G_{a3} > 0 \), \( \alpha = 1.03 \rightarrow 0.4 \).

The measured values of the total pressure \( p_{c30} \) at the DK-500 exit in the case of combustion of the \( \text{CH}_4/\text{H}_2 - \) air mixture allow one to determine the specific impulses in the CSD process with secondary air injection.

4.3. Specific impulse of continuous spin detonation

Let us determine the influence of air addition to detonation products on the specific impulse of the combustor. The thrust force is determined by the formula [5]

\[
F = \frac{\int [p + \rho \cdot v^2 - p_a] dS}{s} = (K' p_{c30} - p_a) S_d, \tag{1}
\]

where \( \rho \) is the density, \( v \) is the velocity, \( p_a \) is the ambient pressure, \( dS \) is the area of the elementary stream tube, \( K = (1 + \gamma \cdot M^2)/(1 + (\gamma - 1) \cdot M^2/2) \gamma(\gamma - 1), M \) is the Mach number, and \( \gamma \) is the ratio of specific heats (\( \gamma \approx 1.25 \)). After the total pressure \( p_{c30} \) and the static pressure \( p_a \) of the products exhausting into the atmosphere is measured at the combustor exit, one can estimate the Mach number from the ratio \( p_{c30}/p_c = [1 + (\gamma - 1) \cdot M^2/2] \gamma(\gamma - 1) \) and then apply Eq. (1) to determine the thrust force \( F \) and the specific impulse based on the fuel flow rate: \( I_{sp,f} = F/(G_f g) \), where \( G_f \) is the fuel flow rate and \( g = 9.81 \text{ m/s}^2 \) is the acceleration due to gravity.

For the \( \text{CH}_4 + 8\text{H}_2 - \) air mixture, Fig. 6 shows the specific impulse based on the fuel flow rate \( I_{sp,f} \) in the CSD regime as a function of the specific flow rate of primary air through the slot \( g_{\delta} \) in the case...
of exhaustion of detonation products into the atmosphere. It is seen that the specific impulse $I_{sp,f}$ monotonically increases with increasing $g_\delta$. At $G_{a3} = 0$ (curve 1 in Fig. 6), the specific impulses at $g_\delta > 3000 \text{ kg/(s·m}^2\text{)}$ reach the asymptotic value $I_{sp,f} \approx 3100 \text{ s}$.

![Figure 6. Specific impulse $I_{sp,f}$ (s) versus the specific flow rate of primary air $g_\delta$, 1 - $G_{a3} = 0$, 2 - $G_{a3} > 0$, $\alpha = 0.53 \to 0.39$, 3 - $G_{a2} > 0$, $\alpha = 1.03 \to 0.4$.](image)

Additional injection of air to detonation products ($G_{a3} > 0$) leads to an increase in the specific impulse $I_{sp,f}$ (curves 2 and 3), which also reaches asymptotically a certain value with increasing $g_\delta$. The maximum value $I_{sp,f} \approx 5200 \text{ s}$ (curve 3) is obtained at $\alpha = 1.03$ and $g_\delta > 3000 \text{ kg/(s·m}^2\text{)}$, which is 50% higher than without secondary air injection. It should be noted that the ratio of the specific impulses at $G_{a3} > 0$ and $G_{a3} = 0$ increases as the parameter $g_\delta$ decreases to 1000 $\text{kg/(s·m}^2\text{)}$. The magnitude of this difference is 72% at $g_\delta = 1750 \text{ kg/(s·m}^2\text{)}$ and $\alpha = 0.9$ and 85% at $g_\delta = 1000 \text{ kg/(s·m}^2\text{)}$ and $\alpha = 0.84$. With a further decrease in the parameter $\alpha$, the difference starts to decrease. Thus, the maximum difference in the specific impulses depends on both parameters: $g_\delta$ and $\alpha$.

5. Conclusions
Continuous spin detonation has been obtained in the DK-500 flow-type annular cylindrical combustor for the $\text{CH}_4 + 8\text{H}_2 + \text{air}$ mixture with addition of secondary air to detonation products up to the value of the air flow rate in the main injection system ($\alpha \approx 1$) for the total equivalence ratio at the combustor exit being reduced to $\phi_e = 0.6 \div 0.4$. It has been found that additional injection of air to detonation products leads to an increase in the pressure in the combustor; as a result, the combustion behind the TDW front is intensified, and the CSD velocity increases. Addition of air to combustion products leads to an increase in the total thrust impulse and to a decrease in the specific flow rate of the fuel. In this case, the range of CSD existence is expanded: the lean limit becomes lower, and the specific flow rates of the mixture components in the combustor increase.

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6. References
[1] Voitsekhovskii B V 1959 Dokl. Akad. Nauk SSSR 129 (6) 1254-1256 [in Russian]
[2] Bykovskii F A and Zhdan S A 2013 Continuous spin detonation (Novosibirsk: Izd. Sib. Otd. Ross. Akad. Nauk) p 423
[3] Bykovskii F A and Zhdan S A 2015 Combust. Expl., Shock Waves 51 (1) 21-35
[4] Bykovskii F A, Zhdan S A and Vedernikov E F 2018 Combust. Expl., Shock Waves 54 (4)
[5] Zuev V S and Makaron V S 1971 Theory of air-breathing and rocket engines (Mashinostroenie)