Continuous spin detonation of poorly detonable fuel-air mixtures in annular combustors

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Abstract. This paper reports on the results of experimental investigations of continuous spin detonation of three fuel-air mixtures (syngas-air, CH₄/H₂-air, and kerosene/H₂-air) in a flow-type annular cylindrical combustor 503 mm in diameter. The limits of existence of continuous detonation in terms of the specific flow rates of the mixtures (minimum values) are determined. It is found that all gas mixtures, including the least detonable methane-air mixture, with addition of hydrogen can be burned in the continuous spin detonation regime.

1. Introduction

Results of experimental and theoretical investigations of continuous spin detonation (CSD) based on Voitsekhovskii’s scheme [1], which are of interest for researchers all over the world, are summarized in the book [2]. The current status of experimental investigations of CSD in flow-type annular combustors (as a variant of an air-breathing engine) for some fuel-air mixtures (FAMs) is analyzed in [3]. It is known that the annular detonation chamber diameter \( d_c \) should be greater than a certain minimum value \( d_c > d_{c,\text{min}} \) for CSD to occur. Obviously, the minimum critical diameter \( d_{c,\text{min}} \) for the least detonable methane-air mixture is very large. The critical diameter for CSD can be reduced by means of special fuel preparation. A well-known method [4] is incomplete thermal oxidation of methane \( \text{CH}_4 + \frac{1}{2}\text{O}_2 = \text{CO} + 2\text{H}_2 \) to a synthesis gas (syngas), which is a mixture of gaseous carbon monoxide (CO) and hydrogen (H₂) with the ratio of their molar fractions 1:2. The first results on CSD in a syngas-air mixture performed in the DK-300 combustor were reported in [5]. Of particular scientific interest is obtaining CSD in a gaseous methane-air mixture and heterogeneous kerosene-air mixture. Detonation burning of these mixtures in plane-radial rocket-type combustor with a diameter \( d_1 = 204 \text{ mm} \) was studied in [6].

The goal of the present work is to obtain, investigate, and analyze the CSD process in a flow-type annular cylindrical combustor 503 mm in diameter (DK-500) for three FAMs: syngas-air, CH₄/H₂-air, and kerosene/H₂-air.

2. Experimental

The DK-500 detonation chamber is a coaxial channel with an outer diameter \( d_c = 503 \text{ mm} \), length \( L_c = 490 \text{ or } 540 \text{ mm} \), and gap \( \Delta = 18 \text{ mm} \) (Fig. 1). The free cross-sectional area of the combustor channel was \( S_\Delta = \pi(d_c - \Delta)^2 = 274.1 \text{ cm}^2 \). Air was fed to the combustor from two receivers 4 over an annular manifold 3 through an annular slot 2 of width \( \delta = 3.5 \text{ mm} \) (the free cross-sectional area was \( S_\delta = \pi(d_c - \delta)^2 - 54.9 \text{ cm}^2 \)). The DK-500 expansion ratio was \( K_S = S_\Delta/S_\delta = 5.0 \).
In experiments with gaseous FAMs, the two-component fuel (CO + 2H₂, CH₄ + 8H₂, or CH₄ + 4H₂) was fed from a receiver 7 over an annular manifold 6 through an injector 5. The injector had 600 orifices with a cross-sectional area 0.35x1.45 mm², which were pairwise aligned at an angle of 90° to the combustor axis. The fuel components were mixed directly in the receiver 7.

In experiments with heterogeneous FAMs, the liquid fuel (aviation kerosene TS-1) was displaced by hydrogen from a flowmeter 13 through a diaphragm 14 into the manifold 6 and then through the injectors 5 into the combustor (right part of Fig. 1). The pressure on the piston was provided by gaseous hydrogen incoming from a receiver 9. Some part of hydrogen through a pipeline and diaphragm 15 was fed to a mixer 16, where bubbling of liquid kerosene was ensured before its injection into the manifold 6. The piston path Lₚ in the flowmeter was measured by a rheostat probe 18.

![Figure 1. Schematic of the experimental setup.](image)

The initial pressures of air in two air receivers were pₑₐ₀ = 30 ± 60 10⁵ Pa. The initial flow rates of air were varied in the interval Gₑ₀ = 6.5 ± 34.5 kg/s, and their initial flow rates Gₐ decreased approximately in proportion to the pressures in the receivers. The initial flow rates of the fuel were varied in the following ranges: a) for CO + 2H₂, Gₑ = 1.2 kg/s; b) for CH₄/H₂, Gₐ₀ = 0.75 ± 1.4 kg/s; c) for kerosene, Gₑ = (0.3 ± 1) kg/s and for H₂, Gₑ₁ = (0.06 ± 0.35) kg/s. The current specific flow rates of the FAMs gₑₙ = (Gₑ + Gₐ)/Sₐ through the cross section of the DK-500 combustor and the fuel-to-air equivalence ratios φ varied in the following intervals: a) gₑₙ = 34 ± 234 kg/(s m²) and φ = 0.81 ± 1.29; b) gₑₙ = 64 ± 850 kg/(s m²) and φ = 0.78 ± 1.02; c) gₑₙ = 230 ± 565 kg/(s m²), φₑ = 0.17 ± 1.3, φ₁ = 0.23 ± 0.51, and m₁ₗ = 8.4 ± 42 %. Here φₑ and φ₁ are the equivalence ratios for kerosene and hydrogen, respectively, and m₁ₗ = Gₑ₁(Gₑ₁ + Gₑ₁) is the mass fraction of H₂ in the two-phase fuel. The detonation products exhausted into the ambient atmosphere with an ambient pressure pₑₐ = 10⁵ Pa.

The process was photographed by a Photron Fastcam SA1.1 675K-M3 high-speed camera in the regime with 40000 frames/s 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, the number of transverse detonation waves (TDWs) n, and the CSD velocity D was similar to that used in [2]. The pressures in the air receivers (pₑ₁ and pₑ₂), receivers of the two-component fuel (pₑₚ), hydrogen (pₑₚₛ), corresponding manifolds (pₑₚₚ and pₑₙ), and also the static (pₑₚ₁, pₑₚ₂, and pₑₚ₃) and total (pₑₚ₃₉) pressures were registered at distances of 15 and 100 mm from the combustor entrance (pₑₚ₁ and pₑₚ₂) and near the combustor exit (pₑₚ₁ and pₑₚ₃) by S-10 pressure sensors produced by the VIKA company.

3. Results of experiments

3.1. CSD in syngas-air mixtures

The DK-500 combustor with the length Lₑ = 540 mm allowed us to obtain multiwave (n = 2 ± 3) CSD regimes with the TDW rotation frequency f = 1.51 ± 2.73 kHz and detonation velocity D = 1.13 ± 1.42 km/s for the CO + 2H₂ + air mixture. Figure 2 shows a fragment of the photographic records of the CSD propagation process at the instant of the transition n = 3 → 2.
Three TDWs with decreasing frequencies $f = 2.73 \to 2.58$ kHz and velocities $D = 1.39 \to 1.31$ km/s were obtained as $g_\Sigma = 234 \to 180$ kg/(s m$^2$) and $\phi = 1.29 \to 1.25$. At $g_\Sigma \approx 180$ kg/(s m$^2$), a transitional process was observed with reduction of the number of TDWs (see Fig. 2). It is seen that the transition $n = 3 \to 2$ occurs extremely rapidly (within one round of the wave). The TDW fronts and attached tails (oblique shock waves in reaction products) move from left to right, burning the mixture fed from the injection system, which is illuminated by products of combustion of a small acetylene-oxygen jet. Two TDWs existed until the end of the experiment in the intervals $g_\Sigma = 180 \to 34$ kg/(s m$^2$) and $\phi = 1.25 \to 1.04$; their frequency changed as $f = 1.86 \to 1.51$ kHz and the CSD velocity changed as $D = 1.42 \to 1.13$ km/s. The TDW front height was $h \approx 13$ cm for $n = 3$ and $h \approx 20$ cm for $n = 2$, whereas the ratio of the TDW height to the distance between the waves was $h/l \approx 1/4$. The TDW rotation frequency $f$ obtained in this experiment is shown in Fig. 6 as a function of the specific flow rate of the mixture $g_\Sigma$ (curve 4).

### 3.2. CSD in methane/hydrogen – air mixtures

One-wave and two-wave CSD regimes with the TDW rotation frequency $f = 0.56 \to 1.66$ kHz and detonation velocity $D = 0.76 \div 1.3$ km/s were obtained for the first time in poorly detonable gaseous mixtures $\text{CH}_4 + 8\text{H}_2 + \text{air}$ ($m_H = 1/2$) and $\text{CH}_4 + 4\text{H}_2 + \text{air}$ ($m_H = 1/3$) in the intervals of the specific flow rates of the mixture $g_\Sigma = 64 \div 850$ kg/(s m$^2$) and equivalence ratios $\phi = 0.8 \to 1.02$.

#### 3.2.1. Fuel with the composition $\text{CH}_4 + 8\text{H}_2$ ($m_H = 1/2$).

CSD in this mixture existed in a wide range of the specific flow rates of the mixture $g_\Sigma = 716 \to 64$ kg/(s m$^2$) as $\phi = 1.02 \to 0.78$. In the intervals $g_\Sigma = 160 \div 716$ kg/(s m$^2$) and $\phi = 0.96 \div 1.02$, regimes with two TDWs and TDW rotation frequency $f = 1.32 \div 1.66$ kHz ($D = 1.04 \div 1.3$ km/s) were observed. At $g_\Sigma = 64 \div 160$ kg/(s m$^2$) and $\phi = 0.78 \div 0.96$, CSD was irregular, and the number of waves alternated between one and two ($n = 2 \leftrightarrow 1$). The range of frequencies was $f = 1.1 \div 1.4$ kHz ($D = 0.86 \div 1.1$ km/s) for $n = 2$ and $f = 0.65 \div 0.87$ kHz ($D = 1.02 \div 1.3$ km/s) for $n = 1$. A typical fragment of the photographic records of CSD is shown in Fig. 3.
Table 1. CSD parameters for two compositions of the methane-hydrogen fuel.

| Fuel          | p_{m_0}/p_a | g_{s}, kg/(s \cdot m^2) | \phi | f, kHz | n | D, km/s |
|---------------|-------------|-------------------------|------|--------|---|---------|
| CН4 +8Н2      | 24 \rightarrow 4 | 716 \rightarrow 160 | 1.02 \rightarrow 0.96 | 1.66 \rightarrow 1.32 | 2 | 1.3 \rightarrow 1.04 |
| CН4 +8Н2      | 4 \rightarrow 2 | 160 \rightarrow 64 | 0.96 \rightarrow 0.78 | 1.4 \rightarrow 0.65 | 2 \rightarrow 1 | 1.1 \rightarrow 1.02 |
| CН4 +4Н2      | 25 \rightarrow 18 | 849 \rightarrow 645 | 0.94 \rightarrow 0.95 | 1.36 \rightarrow 1.33 | 2 | 1.1 \rightarrow 1.04 |
| CН4 +4Н2      | 18 \rightarrow 2.5 | 645 \rightarrow 100 | 0.95 \rightarrow 0.97 | 0.83 \rightarrow 0.56 | 1 | 1.28 \rightarrow 0.84 |

3.2.2. Fuel with the composition CH₄ + 4H₂ (mH = 1/3). For the mixture with this composition in the range of the specific flow rates of the FAM g_{s} = 849 \rightarrow 645 kg/(s \cdot m^2) and \phi = 0.94 \rightarrow 0.95, we obtained two TDWs (n = 2) with a monotonically decreasing (in time) rotation frequency f = 1.36 \rightarrow 1.33 kHz and velocity D = 1.07 \rightarrow 1.05 km/s. The TDW height was estimated as h \approx 25 cm, and the ratio h/l was h/l \approx 1/6. At g_{s} \approx 645 kg/(s \cdot m^2), we observed a transition to the one-wave CSD regime. One TDW existed until the end of the experiment in the intervals g_{s} = 645 \rightarrow 100 kg/(s \cdot m^2) and \phi = 0.95 \rightarrow 0.97; its frequency changed as f = 0.83 \rightarrow 0.56 kHz and the CSD velocity changed as D = 1.28 \rightarrow 0.84 km/s. The TDW front height was h \approx 50 cm, and its ratio to the distance between the waves was h/l \approx 1/3. A fragment of the real-scale photographic records of the one-wave CSD is shown in Fig. 4.

Figure 4. Fragment of the photographic records of CSD in the CH₄ + 4H₂ + air mixture: a) one-wave regime of CSD (g_{s} = 620 kg/(s \cdot m^2), \phi = 0.95, f = 0.826 kHz, n = 1, and D = 1.26 km/s).

The experimental results for CSD in DK-500 for the examined CH₄/H₂ compositions are listed in Table 1, and the TDW rotation frequency f as a function of the specific flow rate of the mixture is plotted in Fig. 6 (points 1 and 2).

3.3. CSD in the heterogeneous kerosene/hydrogen – air mixture

CSD regimes with the number of TDWs from one to five were obtained in the heterogeneous FAM liquid kerosene/H₂ – air in the interval of the specific flow rates of the mixture g_{s} = 230 \div 565 kg/(s \cdot m^2) with the mass fraction of hydrogen in the two-phase fuel being varied in the interval m_H = 8.4 \div 42 %. At g_{s} = 527 kg/(s \cdot m^2), \phi_{H} = 0.32, \phi_{H} = 0.51, and m_H = 42 %, a five-wave CSD regime with the TDW frequency f = 4.86 kHz, detonation velocity D = 1.48 km/s, and TDW front height h \approx 60 \div 70 mm was obtained. At g_{s} = 485 \div 557 kg/(s \cdot m^2), \phi_{H} \approx 0.7, \phi_{H} = 0.38 \div 0.41, and m_H = 21 %, a three-wave CSD regime with f = 2.51 \div 3.04 kHz, D = 1.32 \div 1.6 km/s, and h \approx 100 \div 120 mm was observed (Fig. 5).

At g_{s} = 362 kg/(s \cdot m^2), \phi_{H} = 1.29, \phi_{H} = 0.27, and m_H = 8.4 %, a one-wave CSD regime with f = 1.02 kHz and D = 1.56 km/s was obtained. The number of TDWs and their rotation frequency decrease with decreasing mass fraction of hydrogen in the two-phase fuel and specific flow rate of air, whereas the TDW front height increases. The dependence of the frequency f on g_{s} is shown in Fig. 6 (points 3).
Figure 5. Fragment of the photographic records in the kerosene/H₂ + air mixture; m_H = 21%, g_Σ = 520 kg/(s·m²), \( \phi = \phi_f + \phi_H = 1.08 \), \( f = 3.01 \text{ kHz} \), \( n = 3 \), and \( D = 1.55 \text{ km/s} \).

4. Analysis of results

The TDW rotation frequency \( f \) is plotted in Fig. 6 as a function of the specific flow rate of the mixture \( g_Σ \) for three examined FAMs. In particular, based on this figure, the CSD velocity can be easily determined by the formula \( D = \pi d_c f / n \). It is clearly seen that the TDW rotation frequency and the number of TDWs usually increase with increasing \( g_Σ \) for all FAMs. The number of TDWs increases to two \( (n = 2) \) first for the FAM with the syngas at \( g_Σ \approx 34 \text{ kg/(s·m²)} \), then for the FAM with the fuel \( \text{CH}_4 + 8\text{H}_2 \) at \( g_Σ \approx 160 \text{ kg/(s·m²)} \), then for the FAM with the fuel kerosene/H₂ at \( g_Σ \approx 420 \text{ kg/(s·m²)} \), and finally for the FAM with the fuel \( \text{CH}_4 + 4\text{H}_2 \) at \( g_Σ \approx 645 \text{ kg/(s·m²)} \).

Figure 6. TDW frequency versus the specific flow rate of the mixture in DK-500: 1 - \( \text{CH}_4 + 8\text{H}_2 \), 2 - \( \text{CH}_4 + 4\text{H}_2 \), 3 - kerosene + H₂ \( (m_H = 0.084) \), 4 - CO + 2H₂.

A comparison of frequencies for the aviation kerosene/H₂ – air mixture \( (m_H = 0.084, \text{points 3}) \) and \( \text{CH}_4/H₂ – \text{air mixture (points 1, 2)} \) confirms that the methane/hydrogen – air mixture is the least detonable one. One more feature of CSD for FAMs with the methane-hydrogen fuel observed in Fig. 8 should be noted. In a wide range of the specific flow rates of this mixture \( (160 \text{ kg/(s·m²)} < g_Σ < 645 \text{ kg/(s·m²)}) \), the TDW rotation frequency \( f \) remains almost constant and the number of waves is identical. Low wave velocities for the \( \text{CH}_4/H₂ – \text{air mixture (points 1, 2)} \) – \( D \approx 1.0 \text{ km/s} \) are worth noting. At \( m_H < 0.33 \), this mixture cannot compete with the kerosene-hydrogen mixture. Thus, to reach the TDW frequency \( f \approx 1.3 \text{ kHz} \) in the \( \text{CH}_4 + 4\text{H}_2 – \text{air mixture}, \) the specific flow rate of the mixture should be twice greater than that in the kerosene/H₂ – air mixture. If preliminary incomplete thermal oxidation of methane to syngas is performed \( (\text{CH}_4 + 1/2\text{O}_2 \rightarrow \text{CO} + 2\text{H}_2) \), then CSD in the syngas-air mixture is obtained in DK-500 at the specific flow rates of the mixture smaller by an order of magnitude than that for the \( \text{CH}_4 + 4\text{H}_2 \) fuel (see Fig. 6).
Based on the experimental results [3] and those obtained in the present work, we can conclude that the TDW structures in the case of continuous spin detonation in flow-type annular combustors are enlarged in the following sequence:

\[ \text{H}_2 \rightarrow \text{CO} + 2\text{H}_2 \rightarrow \text{CH}_4 + 8\text{H}_2 \rightarrow \text{kerosene/H}_2 \rightarrow \text{CH}_4 + 4\text{H}_2. \]

5. Conclusions

Thus, multiwave regimes of continuous spin detonation in a gaseous syngas-air mixture, poorly detonable \( \text{CH}_4/\text{H}_2 \)-air mixture, and heterogeneous aviation kerosene/\( \text{H}_2 \)-air mixture were obtained in a DK-500 flow-type annular cylindrical combustor and studied. The limits of CSD existence in terms of the specific flow rate of the fuel-air mixture (minimum values) were determined. The TDW structure in all three examined FAMs is similar to the TDW structure in acetylene-air and hydrogen-air mixtures [3]. It was found that all gaseous FAMs that have been studied up to now, including the least detonable methane-air mixture, with addition of hydrogen can be burned in a flow-type annular cylindrical combustor in the CSD regime. The experimental data obtained in the present study offer a possibility of systematic and targeted investigations of specific features of CSD regimes in heterogeneous fuel-air mixtures in annular combustors of air-breathing engines.

Acknowledgment

This work was supported by the Russian Foundation for Basic Research (Grant No. 16-01-00102a).

6. References

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