Continuous detonation of syngas -air mixtures in an annular flow-type cylindrical combustor

Fedor A. Bykovskii[1], Sergey A. Zhdan[1], Evgenii F. Vedernikov[1],

[1] Lavrentyev Institute of Hydrodynamics SB RAS,

630090, Novosibirsk, Russia

1 Introduction

Activities aimed at developing a scientific basis for detonation engines where the fuel is continuously burned in a traveling detonation wave [1] (the scheme proposed by Academician Voitsekhovskii [2]) have been performed since the 1960s. The practical interest is focused on realization of continuous spin detonation (CSD) of fuel-air mixtures (FAMs) under conditions similar to those in air-breathing engines. CSD regimes in acetylene-air and hydrogen-air fuel-air mixtures in a flow-type annular combustor were obtained for the first time and were studied in [3]. The synthesis gas can become a promising fuel. Various technologies are used to obtain the synthesis gas: methane conversion at high pressures and temperatures in the presence of nickel catalysts ($CH_4 + H_2O \rightarrow CO + 3H_2$), and incomplete thermal oxidation of hydrocarbons ($C_nH_{2n+2} + 1/2nO_2 \rightarrow nCO + (n+1)H_2$) [4]. In existing combustors, the synthesis gas is burned by the mechanism of conventional turbulent combustion. The present activities are aimed at obtaining and determining conditions of existence of continuous detonation of synthesis gas-air mixtures with molar fractions [CO]/[H_2]: 1/2, and 1/3.

2 Experimental Setup

The study was performed in a flow-type axisymmetric annular combustor [3]. The combustor had an annular cylindrical geometry with an outer diameter d_c = 306 mm, length L_c = 570 mm, and annular gap Δ = 16.5 mm (the cross-sectional area of the channel was S_Δ =150 cm^2). Air was fed into the combustor from a receiver with a volume V_{rA} = 43.3 l via an annular manifold through an annular slot of width δ = 3 mm, and the fuel was fed from a receiver with a volume V_{rf} = 13.3 l via an annular manifold through an injector. The injector had 400 orifices 1x0.5 mm^2, pairs of these orifices were aligned at an angle of 90^o, and also at an angle of 45^o to the combustor centerline. The mixture of CO and H_2 was composed directly in the fuel receiver. The initial flow rates of air and fuel were varied within G_{A0} = 3.74 – 1.38 kg/s and G_{f0} = 0.51–0.15 kg/s with the initial pressures in the receivers being p_{rA0} = (29 – 10.6)·10^5 Pa and p_{rf0} = (60 – 27)·10^5 Pa, respectively. The initial values of the fuel-to-air equivalence ratio were ϕ_0 = 0.53 – 1.9. During the time of process recording t = 0.45 s, the air flow rate decreased approximately by a factor of 3.4, and the fuel flow rate was halved. Therefore, the equivalence ratio ϕ was increased during the experiment by a factor of 1.5 – 1.7. The specific flow rates of the mixture in different experiments were varied within g_Σ = (G_A + G_f)/S_Δ = (260 – 34) kg/(s·m^2), where G_A and G_f being the current flow rates of the species. Initiation of the process, its photographic recording, and processing of the signals from the sensors were performed in a manner similar to that described in [3]. The combustion products exhausted into the atmosphere.

3 Experimental results

Within the above-mentioned ranges of the parameters of supplying the species, two wave (n = 2) and one-wave (n = 1) regimes of CD of synthesis gas-air mixtures in transverse detonation waves (TDWs) were obtained for the first time for two examined compositions of the synthesis gas: a) $CO + 2H_2$; b) $CO + 3H_2$. Figure 1 shows fragments of typical photographic records of CD of the $CO + 2H_2$ + air mixture for two wave (a) and one-wave (b) regimes. The duration of the process along the band is 1.63 ms. The TDWs move from left to right.

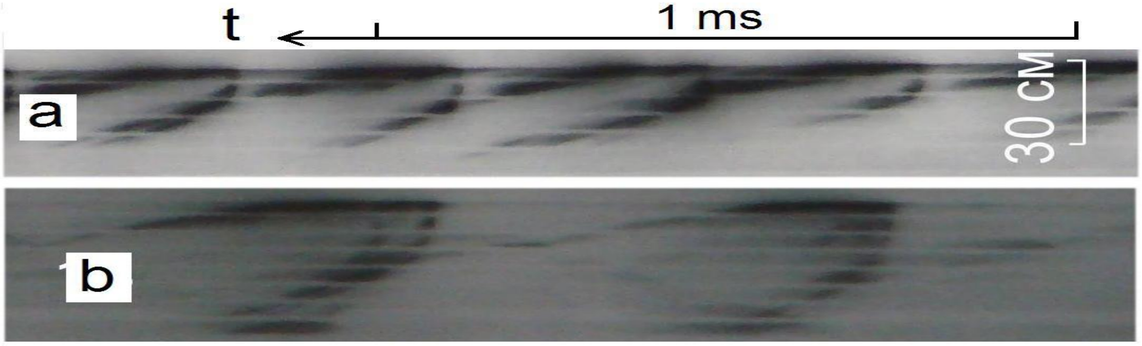

Figure 1. Fragments of typical photographic records of CSD of the $CO + 2H_2$ + air mixture: a) $p_{c1} = 2.5\ 10^5$ Pa, $g_\Sigma = 194$ kg/(s·m^2), $\phi = 0.93$; D = 1.34 km/s, n = 2; b) $p_{c1} = 1.32\ 10^5$ Pa, $g_\Sigma = 80$ kg/(s·m^2), $\phi = 0.99$; D = 1.31 km/s, n = 1.

During the experiment (t ~ 0.45 sec), the specific flow rate of the fuel-air mixture decreases as $g_\Sigma = 218 \rightarrow 74$ kg/(s·m^2), the pressure in the combustor decreases as $p_{c1} = 2.5 \rightarrow 1.3 \cdot 10^5$ Pa, and the equivalence ratio increases as $\phi = 0.89 \rightarrow 1.36$. The velocity of the TDWs first decreases (n = 2, D = 1.37 → 1.27 km/s), drastically increases during the transition to the one-wave regime (n = 2 → 1), and then monotonically decreases until the end of the process: D = 1.52 → 1.28 km/s. The basic parameters of the detonation regimes of examined FAMs for two near-stoichiometric compositions of the synthesis gas, $CO + 2\ H_2$ and $CO + 3\ H_2$, are summarized in Table 1.

Table 1. Parameters of the detonation process in the CO/H_2 /Air mixture.

Fuel	p_{mA}/p_0	g_Σ, kg/(s·m^2)	ϕ	D, km/s	*n*	p_{c1}/p_0
$CO + 2\ H_2$	4.8 →3.2	218 →144	0.89 →1.05	1.37→1.27	2	2.5 →1.83
	3.2→1.87	144→74	1.05→1.36	1.52 →1.28	1	1.83→1.3
$CO + 3\ H_2$	5.1→2.5	240→115	0.9→1.15	1.37→1.22	2	2.7→1.64
	2.5→1.8	115→75	1.15→1.32	1.57→1.32	1	1.64→1.35

It is seen from Table 1 that an increase in the fraction of hydrogen in the synthesis gas leads to formation of stronger transverse detonation waves (TDWs) with a greater CSD velocity and the range of specific flow rates of the mixture for realization of two-wave regimes is extended. For both compositions of the synthesis gas, the increase in the flow rate of the mixture proportionally increases the pressure in the combustor, and the operating frequency of TDW rotation stays in the interval f = (1.27 – 3.02) kHz.

Figure 2 shows the CSD velocity (a) and the TDW rotation frequency (b) as functions of the specific flow rate g_Σ, of the synthesis gas-air mixture. For the synthesis gas composition $CO + 2H_2$ (curves 1), two TDWs are first formed in the combustor (n = 2). As the flow rate g_Σ decreases, the TDW velocity decreases from 1.37 km/s to 1.27 km/s. At $g_\Sigma \approx 140$ kg/(s·m^2), owing to flow reconstruction, only one

TDW propagates in the combustor (n = 1). Its velocity monotonically decreases from 1.52 km/s to 1.28 km/s at $g_{\sum}$ = 74 kg/(s·m^2), $\phi \approx 1.36$.

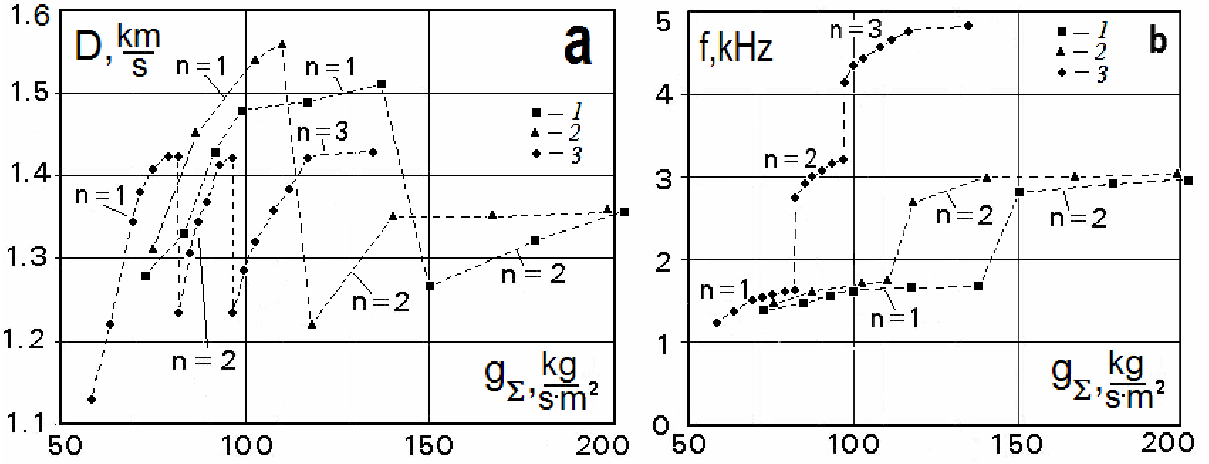

Figure 2. CSD velocity (a) and TDW rotation frequency (b) versus the FAM specific flow rate. (1 - CO + $2H_2$, 2 - CO + $3H_2$, 3 - H_2).

For the synthesis gas composition CO + $3H_2$ (curves 2), two TDWs are first formed in the combustor as well (*n* = 2). As $g_{\sum}$ decreases, the TDW velocity decreases from 1.37 km/s to 1.22 km/s. At $g_{\sum} \approx$ 115 kg/(s·m^2), flow reconstruction occurs, and one TDW propagates in the combustor. Its velocity monotonically decreases from 1.57 km/s to 1.32 km/s at $g_{\sum}$ = 75 kg/(s·m^2). The maximum TDW velocities are reached in the one-wave regime (n = 1): D = 1.52 and 1.57 km/s for the synthesis gas compositions CO + $2H_2$ and CO + $3H_2$, respectively. At an identical number of waves *n* and identical values of $g_{\sum}$, the CSD velocity increases with increasing fraction of hydrogen in the combustible mixture of the synthesis gas and air. For comparison, Fig. 2 also shows the CSD velocity and TDW rotation frequency for a hydrogen-air mixture (curves 3) in a combustor 306 mm in diameter [3]. It is seen that the number of TDWs over the combustor perimeter and their rotation frequency for the H_2 – air mixture increase faster with increasing specific flow rate $g_{\sum}$ than in synthesis gas-air mixtures. Thus, for $g_{\sum}$ = 100 kg/(s·m^2), Fig. 2 yields *n* = 3 and f = 4.3 kHz for the H_2 – air mixture, *n* = 1 and f = 1.68 kHz for the CO + $3H_2$– air mixture, and *n* = 1 and f = 1.63 kHz for the CO + $2H_2$– air mixture. The number of waves changes from two to one (n = 1→ 2) at $g_{\sum} \approx$ 82 kg/(s·m^2) for the H_2 – air mixture, at $g_{\sum} \approx$ 115 kg/(s·m^2) for the CO + $3H_2$– air mixture, and at $g_{\sum} \approx$ 144 kg/(s·m^2) for the CO + $2H_2$– air mixture. It should be noted that flow reconstruction in H_2 – air mixtures after the change in the number of waves occurs fairly rapidly, within 1 - 2 ms, whereas the competition between one and two TDWs in the synthesis gas-air mixture was observed for a rather long time Δt ≈ 50 ms.

In the range of specific flow rates $g_{\sum}$ = 100 ± 20 kg/(s·m^2) and near-stoichiometric fuel-to-air equivalence ratio ($\phi \approx 1$), the CSD velocity in a more chemically active mixture H_2 – air is smaller than in the synthesis gas-air mixtures considered. This apparent contradiction is explained by a greater number of TDWs in the H_2 – air mixture (n = 3, as compared with n = 1 for the synthesis gas-air mixtures). It is only at $g_{\sum}$ < 82 kg/(s·m^2), when a regime with one TDW is established for all mixtures (n = 1), the situation is settled: the TDW velocity is higher in the H_2 – air mixture. In the examined synthesis gas-air mixtures, we measured the detonation front height *h*, which depends on the mixture composition, the number of TDWs, and the values of ϕ and $g_{\sum}$. At n = 2, the value of *h* varied within *h* = 12 – 15 cm, and smaller values of *h* correspond to a greater fraction of hydrogen in the combustible mixture. At n = 1, the values *h* = 18 – 24 cm were observed in near-stoichiometric mixtures. The analysis of CSD parameters for the three examined FAMs allows us to state that it is more difficult to ensure CSD in synthesis gas-air mixtures than in a more chemically active H_2 – air mixture. It is also definitely established that, for identical specific flow rates of synthesis gas-air mixtures, a decrease in the fraction of hydrogen in the synthesis gas composition leads to a decrease in TDW velocity and in the number of TDWs.

The height of the TDW front in the H_2 – air mixture is $h \approx 24/n$ cm for n = (1–3) [3]. It is known that the detonation cell size and the associated size of the shock-detonation waves in the classical gas detonation in premixed FAMs correlate with the chemical activities of the mixtures [5] and increase in the following sequence: $C_2H_2 \rightarrow H_2 \rightarrow CO/H_2$. In CSD regimes in a flow-type annular combustor, however, enlargement of the TDW structure for the same FAMs follows another sequence: $H_2 \rightarrow CO/H_2 \rightarrow C_2H_2$.

At specific flow rates of the mixtures $g_\Sigma = 100$ kg/(s·m^2), the number of waves in the H_2 – air mixture is three times greater (the TDW size is three times smaller) than in the C_2H_2 – air mixture [3], whereas the cell size *a* in the classical detonation in the premixed C_2H_2 – air mixture is 1.5 times smaller than in the H_2 – air mixture [6]. In our opinion, this unexpected result is caused by the dominating influence of physical processes of mixing of the species over the chemical properties of the mixtures in CSD realization in flow-type combustors, in particular, by more intense mixing of hydrogen and air because of the greater difference in jet velocities on the contact boundaries, which determine the turbulence intensity and scale. This assumption is supported by the results of experiments at δ/Δ = 0.26 and δ/Δ = 0.435 with worse mixing, where only one-wave detonation regimes were observed [3].

4 Summary

The regimes of continuous detonation combustion of a synthesis gas-air mixture in transverse (spinning) detonation waves in a flow-type annular cylindrical combustor are obtained for the first time. The limits of detonation existence in terms of the fuel-to-air equivalence ratio (minimum and maximum values) and in terms of the specific flow rates of the species (minimum values) are determined. The maximum velocities of the detonation waves are observed in the case with a moderate excess of the fuel (approximately by 15%) and also in mixtures with the greatest fraction of hydrogen. The structure of the detonation waves and the heights of their fronts for the examined mixtures are close to those determined previously for hydrogen-air mixtures.

5 Acknowledgement

This work was supported by the Program No. 26.3 of the Presidium of the Russian Academy of Sciences, by the Russian Foundation for Basic Research (Grant No. 13-01-00178) and by the Grant of the President of the Russian Federation (No. NSh 247.2012.1).

References

[1] Bykovskii FA, Zhdan SA, and Vedernikov EF. (2006). Continuous Spin Detonations // *Journal of Propulsion and Power.* 22 (6): 1204

[2] Voitsekhovskii BV, Mitrofanov VV, and Topchiyan ME. (1966). Structure of Detonation Front in Gases. Wright-Patterson AFB Rept. FTD-MT-64-527 (AD-633, 821).

[3] Bykovskii FA, Zhdan SA, and Vedernikov EF. (2006). Continuous spin detonation of fuel-air mixtures. *Comb., Expl. Shock Waves*. 42 (4): 463.

[4] Catalysis in C_1 Chemistry. (1983). Edited by W. Keim. D. Reidel Publishing Co., Dordreeht, Holland. 296 p.

[5] Austin JM, Shepherd JE. (2003) Detonations in hydrocarbon fuel blends. *Combustion and Flame*. 132 (1-2): 73.

[6] Vasil'ev AA, Mitrofanov VV, and Topchian, ME. (1987). Detonation Waves in Gas. *Comb., Expl., Shock Waves*. 23 (5): 109.