Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: F A Bykovskii *et al* 2017 *J. Phys.: Conf. Ser.* **899** 042001

Continuous spin detonation of a syngas-air mixture in a plane-radial vortex combustor

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Abstract. Continuous spin detonation in syngas-air mixtures with three different syngas compositions [CO]/[H_2] = 1/3, 1/2, and 1/1 is experimentally studied in a flow-type radial vortex combustor 500 mm in diameter. It is found that all these mixtures with three syngas compositions can be effectively burned in air in the detonation regime. Transverse detonation waves of identical structure are detected. The limits of existence of continuous detonation in terms of the specific flow rates of the mixtures (minimum values) are determined.

1. Introduction

Intense investigations of burning various fuels in a continuously running transverse detonation wave (TDW) (according to Voitsekhovskii's concept [1]) are currently performed. Of interest for practice is continuous spin detonation (CSD) of fuel-air mixtures (FAMs) in flow-type combustors, which are used in air-breathing engines and power engineering facilities. Anthracite and lignite particles were burned in a detonation manner in a flow-type plane-radial vortex combustor 500 mm in diameter (PDK-500) located at the Lavrentyev Institute of Hydrodynamics of the Siberian Branch of the Russian Academy of Sciences [2]. The coal particles were transported to the combustor by a syngas flow with syngas compositions [CO]/[H_2] = 1/3, 1/2, and 1/1, which simultaneously served as a promoter of the chemical reaction in the detonation wave. Of independent scientific interest is burning a mixture of air with syngas containing no coal particles in the PDK-500, which is particularly important because a number of advanced technologies of syngas production have been developed. Depending on the method of syngas production, the ratio [CO]/[H_2] may have different values. Thus, gasification of coal with water vapor ($C + H_2O = CO + H_2$) allows syngas production with [CO]/[H_2] = 1/1; partial oxidation of saturated hydrocarbons ($C_nH_{2n+2} + 1/2nO_2 = nCO + (n+1)H_2$) ensures syngas production with [CO]/[H_2] = 1/1 ÷1/2; finally conversion of saturated hydrocarbons with water vapor ($C_nH_{2n+2} + nH_2O = nCO + (2n+1)H_2$) allows syngas production with [CO]/[H_2] = 1/2÷ 1/3 [3]. As the number of carbon atoms in a hydrocarbon molecule decreases, the amount of released hydrogen increases (the greatest amount of hydrogen is released in the case of methane conversion: 1/3). The goal of the present paper is to obtain and study continuous detonation burning of FAMs based on syngas with the molar fractions [CO]/[H_2] = 1/1, 1/2, and 1/3 in the PDK-500 flow-type combustor.

2. Experimental

The experimental setup and the radial vortex combustor with a diameter d_{c1} = 500 mm and exhaustion toward the center are schematically shown in Fig. 1.

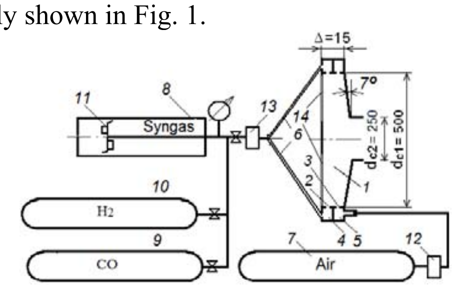

Fig. 1. Experimental setup and combustor.

The experimental combustor *1* is a semi-closed volume bounded by a cylindrical wall and two side walls (one flat wall and one conical wall with an angle $\alpha \approx 7^o$ from the base plane). The chosen geometry of the combustor *1* ensured an approximately constant cross-sectional area along the radius $S_c = \pi \cdot d_{c1} \cdot \Delta = 235.6$ cm^2, where $\Delta = 15$ mm is the distance between the walls near the cylindrical surface of the combustor. The reaction products escaped from the combustor through an orifice with a diameter $d_{c2} = 250$ mm, which was located in the conical wall.

The syngas was fed to the combustor *1* through an injector *2*, which had 150 orifices with a cross-sectional area of 0.5x1 mm^2 uniformly distributed over the cylindrical wall and directed along the radius. Air was supplied to the combustor *1* through 50 channels *3* formed in an annular slot of width $\delta = 5$ mm by ribs of thickness $\delta_r = 1$ mm inclined to the radius at an angle $\beta = 75^o$. The air flow was swirled in the combustor by guiding ribs with the minimum distance between them being 10 mm. The free cross-sectional area of the air slot at the combustor entrance was $S_\delta = (\pi \cdot d_{c1} - 50\ \delta_r) \cdot \delta = 76.04$ cm^2, and the combustor expansion ratio was $K_s = S_c/S_\delta = 3.1$.

Air and syngas were distributed over the orifices by annular manifolds *4* and *5,* respectively. In addition, a more uniform distribution of syngas over the manifold *5* was provided by using 24 tubes *6*. Air was supplied to the manifold *5* from a receiver *7* with a volume $V_{r,a} = 43$ liters, and syngas was supplied to the manifold *5* from a receiver *8* with a volume $V_{r,f} = 13.8$ liters, where it was prepared. Carbon monoxide from a gas holder *9* and hydrogen from a gas holder *10* were fed to the receiver *7,* where they were mixed. First the receiver was filled with carbon monoxide and then hydrogen was added. The gases in the receiver were mixed with the use of the Segner wheel *11* with blades on both arms. Hydrogen formed jets and rotated the wheel, while the blades provided the motion of the mixture in the axial direction. Thus, intense mixing of the gases was ensured. The time of the mixture formation (from the beginning of its preparation to its injection to the combustor) was 5 minute or more; therefore, the combustible components were well mixed over the entire receiver volume. An independent criterion of good mixing was the flow rate coefficient *c* [4]*,* which had the same value for a particular mixture in different experiments. Air and syngas were injected into the combustor after opening of valves *12* and *13,* whose actuation time was defined by a specially programmed device on the control panel.

As the pressures in the receivers decreased, the flow rates of air and syngas also decreased: $G_a = 7.8 \rightarrow 0.76$ kg/s, $G_f = 1.2 \rightarrow 0.8$, $0.67 \rightarrow 0.076$, and $0.45 \rightarrow 0.05$ kg/s for the syngas compositions $[CO]/[H_2]$ = 1/1, 1/2, and 1/3, respectively. The specific flow rates of air and fuel through the combustor cross section stayed within the interval $g_\Sigma = (G_a + G_f)/S_c = 340 \div 40$ kg/(s·m^2). The fuel-to-air equivalence ratio was almost constant: $\phi = 0.62$, 0.57, and 0.47 ± 0.02 for the syngas compositions $[CO]/[H_2]$ = 1/1, 1/2, and 1/3, respectively. CSD was initiated in the combustor by means of burning an aluminum foil strip by electric current with an energy of about 5 J. The combustion products escaped into the atmosphere with an ambient pressure $p_a = 10^5$ Pa.

The process was photographed through two windows *14* located diametrically opposite along the combustor radius by a Photron FASTCAM SA5 type 775K-M2 high-speed video camera operating at 420000 frames per second. From each frame consisting of 16 pixels over the width of the window, only one pixel was chosen with the use of a special code written in the C^{++} programming language, and this pixel was then combined with single pixels chosen from other frames. As a result, the flow in the wave-fitted coordinate system was constructed. However, to obtain a real image of the TDW structure, the linear pattern should be rolled into a ring with retaining the scale of the examined object.

The pressures in the air and fuel receivers and manifolds ($p_{r,a}$ and $p_{r,f}$, $p_{m,a}$ and $p_{m,f}$, respectively), and also the pressures in the combustor (p_{ci}, where *i* is the number of the sensor located at a distance of 5, 47, 87, and 126 m from the cylindrical surface) were recorded by pressure sensors produced by the Wika company (Germany). The signals from the pressure sensors were recorded and processed on a computer.

3. Results of experiments

Stable CSD was observed in all experiments with burning FAMs consisting of air and syngas with three different compositions. A fragment of the photographic records of CSD for the CO + H_2 – air mixture is shown in Fig. 2. The linear sizes of the waves in the tangential direction near the cylindrical surface are corrected to the combustor diameter.

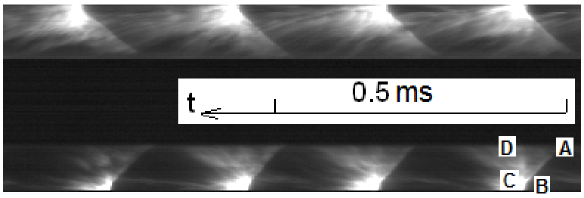

Fig. 2. CSD in the (CO+H_2) – air mixture (fragment of the photographic records), g_Σ = 294 kg/(s·m^2), ϕ = 0.62, $p_{m,a}$ =13.1·10^5 Pa, p_{c1} = 3.4·10^5 Pa, D = 1.67 km/s, and n = 4.

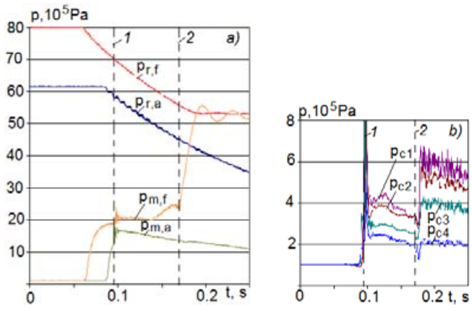

Fig. 3. Pressure oscillograms in the system of injection of the fuel components (a) and in the combustor (b).

The mixture is burned in four (n = 4) TDWs moving with a velocity D = 1.67 km/s. These waves move from left to right in the lower window and in the opposite direction in the upper window. The detonation front BC is the result of irregular reflection of the precursor AB from the cylindrical wall (Mach stem). A tail CD (shock wave in the products) emanates from the triple point C. A similar structure was observed in the case of CSD in homogeneous and two-phase mixtures in combustors of similar geometry [4]. A similar wave structure was also detected in FAMs containing syngas with the compositions CO + 2H_2 and CO + 3H_2. The ratio of the height of the front BC (h) to the distance between the waves (l) was h/l ≈ 1/15.

The oscillograms of the pressures in the system of injection of the fuel components and in the combustor for the experiment illustrated in Fig. 2 are shown in Fig. 3. In this experiment, the orifices of the fuel injectors were choked. As a result, the pressure sensors measured the pressures before the instant of initiation (*1*), in the CSD regime (time interval *1-2)*, and during exhaustion of cold air (after the time instant marked by *2*). The injection system displayed only a minor response to CSD initiation, and the pressure in the combustor first increased due to exhaustion of the cold mixture and then decreased. Another increase in pressure was observed after injector choking. The pressures decrease toward the combustor center. The processes in the injection system and in the combustor at the instant of CSD initiation and existence for other syngas compositions were similar to the situation described above. The main parameters of the CSD regimes are listed in Table 1.

Table 1. Basic parameters of the CSD regimes for three syngas compositions.

syngas	G_A, kg/s	G_f, kg/s	g_Σ, kg/(s·m^2)	ϕ	$p_{m,a}$	p_{c1} ·10^5 Pa	D, km/s	n
[CO]/[H_2]	7.8- 5.98	1.0- 0.63	364- 294	0.61- 0.63	17- 13.0- 13.1	4.2- 3.4 6.4	1.86- 1.67 -	3- 4 -
[CO]/[2H_2]	7.8- 0.87	0.67- 0.08	354-40.3	0.57	16.7- 2.5	4.6- 1.6	1.87- 1.97	3- 1
[CO]/[3H_2]	7.6-0.9	0.45- 0.05	341-41	0.48- 0.46	16.3- 2.2	4.4- 1.07	1.88- 1.55	3- 2

For the [CO]/[H_2] composition, the flow parameters after CSD failure are also given.

4.Analysis of results

For similar specific flow rates of the combustible mixture, the CSD regime was found to be weakly dependent on the syngas composition. For close values of the equivalence ratio, an identical number of waves (n =3 or n = 2) and similar detonation velocities were obtained in both more and less chemically active syngas compositions. Apparently, the key role is played by acoustic phenomena in the combustor because the flow in the radial direction is subsonic. Figure 4 shows the detonation velocity (D) and the number of TDWs ПДВ (n) as functions of the specific flow rate of the fuel (g_Σ).

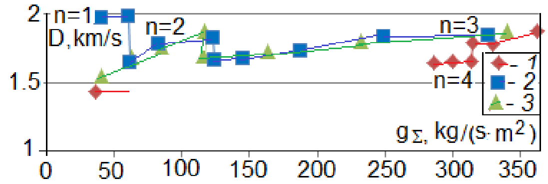

Fig. 4. Detonation velocity and number of TDWs versus the specific flow rate of the fuel for three syngas compositions: *1* -[CO]/[H_2], *2* - [CO]/[2H_2], *3* - [CO]/[3H_2].

During the experiments, the value of g_Σ decreased with decreasing flow rates of the FAM components. At high values of g_Σ, elevated detonation velocities and the greatest number of TDWs were observed. As previously [4], the detonation velocity decreased if the number of TDWs was fixed and the specific flow rate decreased. Moreover, when a certain value of g_Σ was reached, the number of TDWs also decreased (which was accompanied by a drastic increase in velocity). This tendency was clearly observed for the syngas compositions *2* and *3,* whereas the process for the syngas composition *1* displayed an anomalous behavior in the region $g_\Sigma \approx 300$ kg/(s·m^2): the number of waves increased from three to four. Further investigations are needed to explain this phenomenon. Nevertheless, the number of TDWs regularly decreased by the end of the experiment (when the lower limit in terms of g_Σ was approached); the extreme left point for the syngas composition *1* is taken from a different experiment. The minimum values of $g_{\Sigma min}$ were found below which the CSD process ceased (see also Table 1).

As previously [4], the pressures near the cylindrical surface of the radial combustor in experiments without CSD for all examined FAMs were higher than the pressures in the CSD regime with the same specific flow rates g_Σ (approximately by a factor of 2). The reason is the greater value of the centrifugal force in the case of cold gas exhaustion as compared to exhaustion of less heavy hot CSD products. Based on the pressure difference in the air channels ($p_{m,a}/p_{c1}$), it is seen (see Fig. 2 and Table 1) that critical exhaustion of air in the combustor occurs. Further investigations are required to reduce the pressure difference with retaining stable CSD.

Thus, multiwave CSD regimes in mixtures of air with the syngas compositions [CO]/[H_2] = 1/3, 1/2, and 1/1 were obtained for the first time in a plane-radial vortex combustion 500 mm in diameter. The structure of the detonation waves and the heights of the detonation fronts in the examined FAMs are similar to those observed previously for gaseous (methane-air) and heterogeneous kerosene-air and coal-air) mixtures [4].

Acknowledgment

This work was supported by the Russian Foundation for Basic Research (Grant No. 14-08-00080a).

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