Detonation combustion of a hydrogen-oxygen gas mixture in a plane-radial chamber with exhaustion toward the periphery

F.A. Bykovskii, S.A. Zhdan, E.F. Vedernikov, A.N. Samsonov, and E.L. Popov
Lavrentyev Institute of Hydrodynamics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, 630090, Russia

1 Introduction

Continuous spin detonation (CSD) of fuel-air and fuel-oxygen mixtures in annular cylindrical combustors is intensely studied by many researchers. Up to now, investigations in plane-radial combustors (PRC) with exhaustion toward the periphery have been performed only in Russia. The first PRC for detonation combustion designed by Voitsekhovskii [1] was constricted at the exit and operated on a preliminary prepared acetylene-oxygen mixture. Investigations in the PRC with separate injection of the fuel and oxidizer and without constriction at the exit were continued at the Lavrentyev Institute of Hydrodynamics of the Siberian Branch of the Russian Academy of Sciences (LIH SB RAS) [2-4]. In those studies, CSD and pulse detonation (PD) regimes were observed in acetylene-oxygen and hydrogen-oxygen mixtures in a PRC with an inner diameter (injector diameter) of 20 mm and outer diameter (exhaustion of detonation products) of 40, 60, or 80 mm. There is a recent publication of Higashi et al. [5] who obtained detonation regimes in experiments with a hydrogen-air mixture in a PRC connected to a compressor and a turbine.

Previously, it was shown that the detonation combustion of acetylene-oxygen and hydrogen-oxygen mixtures in the regime of oxygen ejection [6] can be carried out in a flow-through annular cylindrical combustor with diameter of 100 mm and channel expansion. Similar regimes were obtained in the combustor with diameter of 306 mm for hydrogen and synthesis gas-air mixtures in the regime of air ejection [4,7]. In these papers, the authors obtained the regimes of CSD and PD, determined the conditions and limits of existence of these detonation regimes with respect to the geometry of combustor and the system of injection of mixture components, considered the structure of detonation waves and flow in their vicinity.

The goal of the present paper is to obtain and study the structure of detonation waves in a PRC with exhaustion of gaseous hydrogen and oxygen flows toward the periphery and also to check the scale effect; the inner diameter of the combustor is d_{c1} = 100 mm and the outer diameter is varied in the interval d_{c2} = 120÷300 mm. Consider the modes of forced oxygen supply and its ejection.

2 Combustor and test technique

2.1 Mode with forced oxygen supply

The experiments were performed in a PRC with an inner diameter d_{c1} = 100 mm and exhaustion toward the periphery (Fig. 1a). The distance between the flat walls was Δ = 5 or 10 mm. The outer diameter of the annular orifice d_{c2} for exhaustion of detonation products was varied: d_{c2} = 120, 150, 200, or 300 mm. The distance between the flat PRC walls was much smaller than the PRC diameters: $\Delta \ll d_{c1} < d_{c2}$. For the PRC with d_{c2} = 300 mm (Δ = 10 mm), the channel could be uniformly constricted toward the exit to Δ^1 = 3.3 mm to ensure a constant area of the circular cross section of the channel S_Δ = 31.4 cm^2 = const.

Separate injection of hydrogen and oxygen into the PRC toward the periphery was performed through injectors uniformly distributed over the circumference on the cylindrical wall and generating a system of intersecting jets to provide mixing of the species near this wall. The total cross-sectional area of the injectors was S_f = 34.2 mm^2 for hydrogen and S_{ox} = 60.8 mm^2 for oxygen. Hydrogen was injected from a receiver with a volume $V_{r,f}$ = 1.95, 4.2, or 10 liters; the volume of the oxygen receiver was $V_{r,ox}$ = 4.2 or 1.95 liters. The initial pressure was $p_{r,f0}$ = (30÷48)·10^5 Pa in the hydrogen receivers and $p_{r,ox0}$ = (30 ÷

Correspondence to bykovskii@hydro.nsc.ru

52)·10^5 Pa in the oxygen receivers. The initial flow rates of the $H_2 - O_2$ mixture varied in the following ranges: G_{f0} =31.2 ÷ 90.1 g/s (hydrogen) and G_{ox0} = 363 ÷ 576 g/s (oxygen). The current flow rates of the gases were determined on the basis of pressure reduction in the oxygen and hydrogen receivers ($p_{r,ox}$ and $p_{r,f}$) [4]. The specific flow rate of the mixture was $g_{\sum} = (G_f + G_{ox})/S_{\Delta}$ = 13.7 ÷ 336 kg/(s·m^2), and the fuel-to-oxidizer equivalence ratio was ϕ = 0.26 ÷ 1.7. Here $S_{\Delta} = \pi d_{c1}\cdot\Delta$ is the area of the PRC entrance.

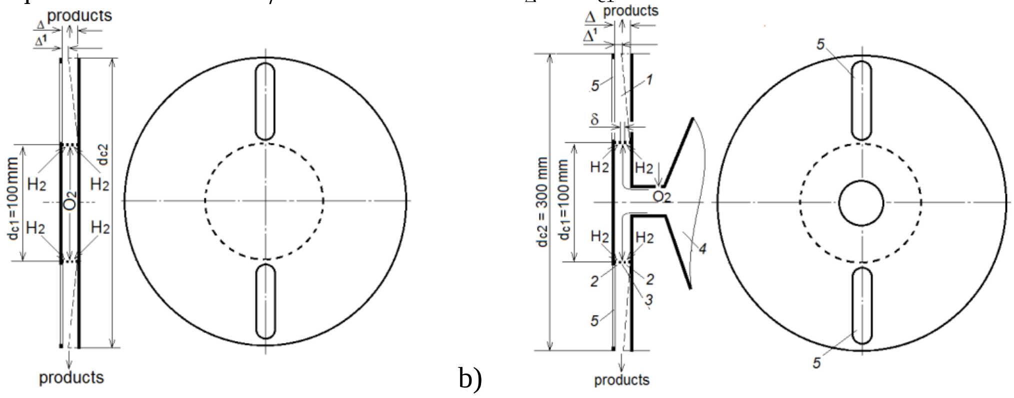


Figure 1. Schemes of the PRC with outflow to the periphery; a) with a forced supply of oxygen, b) with ejection of oxygen.

The process was initiated near the flat wall at a distance of 20 mm from the PRC entrance by blasting an aluminum foil strip by electric current (the energy release was approximately 1 J). The initiation system triggering was synchronized with injection of oxygen into the combustor, which took place later than hydrogen injection. The products escaped into the atmosphere with the ambient pressure $p_a = 1.0\cdot10^5$ Pa. The process was observed through two plexiglas windows 95 mm long and 10 mm wide, which were mounted in the radial direction in one of the flat walls of the combustor and covered almost the entire flow field. It was only a small flow region near the injectors (at a distance of 5 mm) that could not be visualized. The flow along the windows was illuminated by thin acetylene filaments injected exactly in this blind part of the channel.

2.2 Mode with oxygen ejection

The investigation was carried out in the PRC *1* with exhaustion toward the periphery with the diameter of cylindrical surface of d_{c1} = 100 mm and outer diameter of flat walls of d_{c2} = 300 mm, the distance between them was Δ = 12 or 7 mm (Fig. 1b). In a series of experiments, the distance between the walls was uniformly decreased to the combustor exit from Δ = 12 mm up to Δ^1 = 5.3 mm. The area of circular cross-section of the PRC channel at Δ = 12 мм = const increases down the flow from the area of cylindrical surface ($S_{\Delta} = \pi\cdot d_{c1}\cdot\Delta$ = 37.7 cm^2) proportionally to the radius. The cross-section of a constricting channel also increases, and at the PRC exit it is S_{Δ}^1 = 50 cm^2. Thus, in both cases, the PRC has a channel with the area expanding to the exit. Hydrogen was injected from a receiver with a volume $V_{r,f}$ = 4.2 liters through injectors *2* uniformly distributed over the cylindrical combustor wall at a distance of 0.5 mm from the slot for oxygen injection and directed downward the flow at an angle 45° to the axis and generator of cylindrical surface of the PRC. Oxygen was injected into the PRC through the annular slot *3* of width δ = 2 mm (the cross-section is $S_{\delta} = \pi\cdot d_{c1}\cdot\delta$ = 6.28 cm^2). It was exhausted from the receiver *4* of volume V_o = 40 liters with the opposite end of the receiver contacting the ambient air (it is not shown in Fig. 1b) by the whole area of its cross-section, i.e., 415 cm^2. A necessary amount of oxygen was injected into the receiver (the equivalence ratio is $\phi \leq 1$) during the whole experiment. The initial hydrogen pressure in the receiver was set $p_{r,f0} = 12\pm1\cdot10^5$ Pa, Here the initial flow rate of H_2 was $G_{f0} \approx$ 19±2 g/s, and the current flow rates G_f reduced by a factor of 10 during the process (0.4 s). As a results, specific hydrogen flow rates through the PRC cross-section at diameter d_{c1} varied within the range $g_f = G_f/S_{\Delta}$ = 0.5 ÷ 7.4 kg/(s·m^2). The oxygen flow rate in the PRC was estimated depending on experiment conditions.

2.3 Registration system

The process in the PRC was photographed by a Photron FASTCAM SA5 high-speed camera with a frequency from 420000 to 620000 frames per second. By processing these frames along the windows in accordance with a specially developed program, the overall flow pattern in the wave-fitted system was obtained. The photographic records were used for finding the time Δt when the detonation waves arrived opposite the window, which allowed unique determination of their frequency f: *f = 1/Δt*. In the case of

CSD, it was also possible to calculate the velocity D of motion of transverse detonation waves (TDWs) with respect to the cylindrical surface diameter d_{c1}: $D = \pi \cdot d_{c1}/(n \cdot \Delta t)$. Here n is the number of TDWs along the combustor circumference.

The following pressure measurements were performed: pressures in the hydrogen ($p_{r,f}$) and oxygen ($p_{r,ox}$) receivers, pressures in the corresponding manifolds ($p_{m,f}$ and $p_{m,ox}$), static pressures p_{c1} in the combustor at a distance of 10 mm from the cylindrical surface, static (p_{c2}) and total (p_{c20}) pressures (with the use of the Pitot probes) at a distance of 50 mm from the cylindrical surface, and the static (p_{c3}) and total (p_{c30}) pressures at the PRC exit (see Fig. 1). The pressure measurements were performed by certified pressure probes with the accuracy class of 0.5% produced by the Trafag company (Switzerland).

3 Experimental results and their analysis

3.1 Mode with forced oxygen supply

Regimes of continuous multifront detonation (CMD) with opposing TDWs and CSD were obtained in PRC with Δ = 10 mm and d_{c2} = 300 mm for the ranges of the specific flow rates of the mixture $H_2 - O_2$ g_{Σ} = 13.7 ÷ 297 kg/(s·m^2) and equivalence ratios ϕ = 0.26 ÷ 1.7 (Figs. 2a and 2b, respectively).

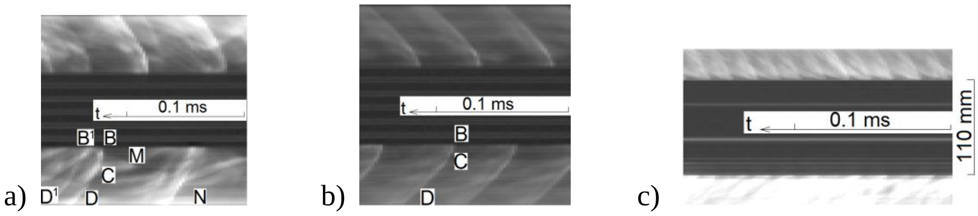


Figure 2. Typical photographic records (fragments): a) – CMD; Δ = 10 mm, d_{c2} = 300 mm, g_{Σ} = 157 kg/(s·m^2), ϕ = 1.51, f = 19.3 kHz; b) – CSD; Δ = 10 mm, d_{c2} = 300 mm, g_{Σ} = 87 kg/(s·m^2), ϕ = 0.85, n = 3, f = 18.4 kHz, D = 1.93 km/s; c) – CSD; Δ = 5 mm, d_{c2} = 200 mm; g_{Σ} = 323 kg/(s·m^2), ϕ = 1.0, f = 68.9 kHz, n = 11, D = 1.97 km/s.

In CMD mode the detonation and shock waves and also the flow in the vicinity of these waves are clearly seen in a fig. 2a. Before its collision, the detonation wave front **BC** of height $h \approx 35$ mm with an adjacent tail **CD** is accelerated until it reaches the maximum velocity. After the "forward" TDW collides with the "opposing" TDW (outside the frame), it degenerates into a shock wave $\mathbf{B^1D^1}$ and moves in the opposite direction, first over the detonation products away from the forward wave and then with a growing velocity over the mixture layer increasing until the instant of the next collision at another point. The same occurs for the "opposing" TDW. The supersonic flow of the products is decelerated in shock waves MN, which penetrate into the PRC up to its entrance. The process is extremely irregular in terms of both the TDW structure and the flow near the TDW. As the specific flow rate of the mixture decreases, the CMD regime with opposing TDWs persists down to g_{Σ} = 105 kg/(s·m^2) and then transforms to the regular CSD regime (Fig. 2b). The layer of the mixture ahead of the front BC is sufficiently stable ($h \approx 15$ mm); relative to the distance to the next wave *l*, the ratio is $h/l \approx 1/7$. Weak acoustic waves are observed at g_{Σ} < 43.3kg/(s·m^2).

Figures 3a and 3b show the pressure oscillograms in the injection system and PRC during the experiment whose photographic records (fragments) are presented in Fig. 2. It is seen that the pressure $p_{r,f}$ and $p_{r,ox}$ in the receivers decreases. The flow of the products near the sensors (p_{c2}) and p_{c20} is supercritical.

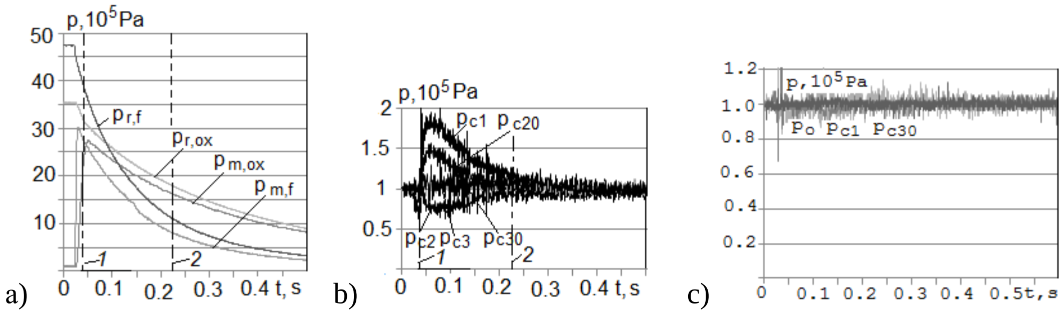


Figure 3. Pressure oscillograms in the injection system (a) and PRC (b); *1*-initiation of detonation, *2* – pressures corresponding to the fragment in Fig. 2b; c) – pressure in the chamber and at the inlet to the oxygen gap (p_o) and in the PRC (p_{c1} and p_{c30}) during ejection.

At the PRC exit, the pressure shock moves from outside into the channel, the flow turns to the subcritical state, and the total pressure p_{c30} becomes almost equal to the static pressure p_{c3}. Significant pressure

oscillations are detected in the PRC, but these are not true values because of the inertia of the sensors. The injection pressures are sufficiently high to ensure the necessary flow rates of the mixture components; therefore, the processes in the combustor do not produce any significant effect on the injection system.
As the PRC channel is constricted from Δ = 10 to Δ^1 = 3.3 mm (see Fig. 1a), the conditions in the combustor and the detonation process become essentially different. The static pressure in the combustor is approximately doubled, whereas the pressure at the combustor exit remains at the atmospheric level. Continuous spin detonation is observed in the intervals g_Σ = 163→45 kg/(s·m^2) and ϕ = 1.39→0.5. The mixture burns in a greater number of TDWs (n = 8→5) with TDW velocities D = 2.09→1.5 km/s. The arrow indicates the direction of parameter changing during the experiment.
In order to minimize the length of the RPC (outer diameter of the d_{c2} chamber), the outer diameter of the chamber was reduced to d_{c2} = 200 mm, and the length of the RPC channel was halved (to 50 mm). The nature of the process in the PRC has not changed. Initially, there was a regime of CMD, and then-CSD. The change of modes occurred somewhat earlier - at g_Σ = 115 ± 5 kg/(s·m^2). However, in the RPC with Δ = 5 mm and d_{c2} = 200 mm for all g_Σ = 13.7 ÷ 336 kg/(s·m^2), only CSD regimes were observed (Fig. 2c).
Based on the number of TDWs and their velocity, it is seen that only a partial scale effect is observed in the PRC with exhaustion toward the periphery, in contrast to annular cylindrical combustors with channel expansion. For example, one wave (n = 1) rotating with respect to the inner diameter d_{c1} with a velocity D = 1.11 km/s was obtained in the PRC with d_{c1} = 20 mm, Δ = 5 mm, L_c = 10 mm, and specific flow rate g_Σ = 132 kg/(s·m^2) [3]. In this work, five waves (n = 5) rotating with respect to the inner diameter d_{c1} with a velocity D = 1.75 km/s were obtained in the PRC with d_{c1} = 100 mm, Δ = 5 mm, L_c = 10 mm, and g_Σ = 132 kg/(s·m^2). The scale effect in terms of the number of waves does exist (n = 5 = 100/20), but the TDW velocities are significantly different: the detonation velocity in the PRC with the greater diameter is appreciably higher. Obviously, the smaller the inner diameter of the PRC, the greater the influence of centrifugal forces on the detonation products behind the TDW front. Therefore, the pressure of the detonation products behind the TDW front in the PRC with d_{c1} = 20 mm decreases more intensely and, hence, the TDW velocity decreases. The existence of a minimum PRC diameter d_{c1min} at which CSD can still occur raises no doubts. Even for preliminary prepared and motionless mixtures, there exists a minimum diameter of the cylindrical surface around which the classical detonation wave can pass [8]. As the PRC diameter increases, the centrifugal forces acting on the products become less intense, and the CSD realization conditions approach those existing for the annular cylindrical combustor with channel expansion.
Reconstruction of TDWs and the flow in their vicinity in the PRC plane and in the wave-fitted system for three TDWs is shown in Fig. 4. This reconstruction is based on the right-side fragment of the photographic records in Fig. 2b, which was scaled relative to the inner diameter of the combustor d_{c1} = 100 mm.

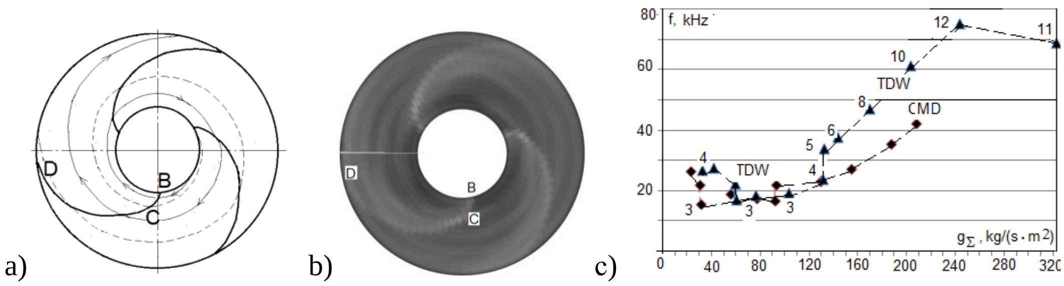


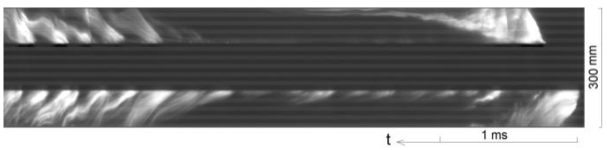
Figure. 4. Reconstruction of TDWs and the flow in their vicinity in the PRC plane and in the wave-fitted system; a) - manual, b) – according to the program (see Fig. 2b); c)- TDW frequencies in the PRC for the CSD and CMD regimes; ♦ - Δ = 10 mm, ▲- Δ = 5 mm; the numbers from 3 to 12 indicate the number of TDWs.

The contact line near the PRC entrance is the boundary between the fresh mixture and products; further downstream, this line serves as the boundary between the layers of the detonation products. It is seen that the streamline crosses the waves many times (in the present case, four times). This is not good from the energy point of view because of the increase in the entropy of the products. Therefore, it is reasonable to reduce the PRC length without large changes in the detonation process. If the tail at the point **D** in the PRC is assumed to degenerate into an acoustic wave, then its velocity in the normal direction should be close to the velocity of sound in the products $D^1_n = D\cdot(r_{c2}/r_{c1})\cdot\sin\alpha \approx 1.3$ km/s [4], where $\alpha = 13^o$ is the angle between the tail and the tangential line to the circumference.

The TDW frequencies in the PRC with d_{c2} = 200 mm and Δ = 5 mm (CSD) and Δ = 10 mm (CMD) are plotted in Fig. 4c as functions of the specific flow rate of the mixture g_{Σ}. There are only minor changes in the equivalence ratio in the present case: ϕ = 0.85÷1.08. For both combustors, the frequency of the rotating waves decreases with reduction of the specific flow rate of the mixture. It is only at small specific flow rates (g_{Σ} = 30±10 kg/(s·m^2)) that the TDWs degenerate into acoustic waves, and the number of TDWs increases from three to four. The CMD regime is observed in the interval g_{Σ} = 208 → 93 kg/(s·m^2), and it transforms to the CSD regime as g_{Σ} = 93 → 23 kg/(s·m^2). The mechanism of the emergence and stable realization of the CMD regime and its transformation to the CSD regime was not clarified. It should be noted that the TDW velocities in all regimes stay within narrow limits D = 2.0 ±0.2 km/s despite wide-range changes in the equivalence ratio ϕ = 1.6 ÷ 0.5, respectively. This means that the flow gas dynamics produces a dominating effect on the process in this range of equivalence ratio variation as compared to chemical physics in the detonation wave front. The imperfection of continuous detonation is estimated by the ratio D/D_{CJ} = 0.6÷0.8, where D_{CJ} is the velocity of the ideal Chapman-Jouguet detonation for the present composition of the mixture. Smaller values of D/D_{CJ} correspond to greater values of ϕ.

3.2 Mode with oxygen ejection

The most important result of the work is the experimental confirmation of the possibility of the existence of continuous spin detonation in ejectors, in this case, PRC. The fragment of photographic records of the process developing from the instant of initiation (bright flash of mixture in the combustor) for Δ = 12 mm and Δ^1 = 5.3 mm is illustrated in Fig. 5a. Figure 2b shows an enlarged fragment of one detonation wave (see Fig. 5 a, to the left) recorded in the lower window and reduced to the length scale with respect to the radius and cylindrical surface of the PRC.

a) 

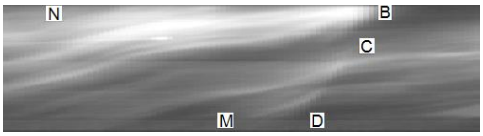
b) 

Figure. 5. The instant of process initiation and transformation to CSD for Δ = 12 mm, Δ^1 = 5.3 mm - a); g_f = 4.17 kg/(s·m^2), n = 1, D = 1.39 km/s (f = 4.44 kHz) –b).

It is seen that the time duration from the instant of initiation up to the TDW development is 3 ms. The detonation regime with one TDW was observed for about 100 ms within the range of hydrogen flow rate G_f = 15.7 → 9.75 g/s (g_f = 4.17 → 2.6 kg/(s·m^2)). The arrow shows the decrease of hydrogen flow rate during the experiment. The detonation velocity with respect to the PRC end wall varied in the interval D = 1.3 ÷ 1.43 km/s (f = 4.17 ÷ 4.56 kHz). The structure of detonation and shock waves and also the flow in the vicinity of these waves are seen most clearly in the enlarged fragment (see Fig. 2b). The process of CSD is irregular enough both in structure of the TDWs and flow in the vicinity of these waves. In the region of hydrogen flow rates G_f = 9.75 → 5 g/s (g_f = 2.6 → 1.33 kg/(s·m^2)), the TDWs were degenerated into acoustic ones with radial displacement of compression wave **MN** and periodic (f = 4.07 → 3.8 kHz) burning of the mixture after reflection of longitudinal compression wave from the PRC end (e.g., see Fig. 5). At G_f = 5 → 1.6 g/s (g_f = 1.33 → 0.42 kg/(s·m^2)), weakening acoustic waves were observed during the combustion.

Figure 3c shows the oscillograms of static pressure in front of and behind the annular slot *3* p_o and p_{c1} obtained in the experiment. The fragments of photographic records of the experiment are illustrated in Fig. 5. Note that the mean value of static pressure of oxygen at the slot entrance, in the combustor and in the receiver have almost identical values – $p_o \approx p_{c1} \approx p_{c30} \approx 1{\cdot}10^5$ Pa. Only the instant of initiation of the mixture collected initially in the PRC and from spinning TDWs is characterized by pressure variations about this mean value.

As a constant gap Δ = 12 mm was adjusted, the regime of CSD with one TDW (n = 1, D = 1.54 km/s and f = 4.9 kHz) had existed for 2 ms immediately after initiation at $G_f \approx$ 19.5 g/s ($g_f \approx$ 5.17 kg/(s·m^2)). Then with decreasing of G_f = 19. 5 → 11.9 g/s (g_f = 5.17 → 3.16 kg/(s·m^2)), the regime with two weak near sonic waves (n = 2, D = 0.75 → 0.69 km/s and f = 4.8 → 4.4 kHz) was set. As the PRC gap was decreased to Δ = 7 mm, one could observe a two-wave regime of the CSD (n = 2, D = 1.45 → 1.53 km/s, f = 9.26 → 9.77 kHz) in a narrow range of hydrogen flow rates G_f = 16.3 → 15.9 g/s (g_f = 7.4 →7.23

$kg/(s\cdot m^2)$). In the region of hydrogen flow rates $G_f = 15.9 \rightarrow 1.7$ g/s ($g_f = 7.23 \rightarrow 0.77$ $kg/(s\cdot m^2)$), the TDWs were degenerated into acoustic ones, the compression waves **MN** began to displace radially and burned the mixture periodically with frequency f = 4.5 → 3.4 kHz after they reflected from the cylindrical surface of the combustor.

Due to the fact that the CSD is obtained in the experiments described above, there is a mechanism of inhausting the outside gas into the PRC. It is found in the experiment with annular cylindrical combustors having channel expansion [4] and is verified in the PRC in the present work. The radial gas velocity in the combustor $v_r = dr/dt$ determined in accordance with the photographic records of luminescent gas particles moving along the window was $v_{r,m} \approx 350$ m/s (see Fig. 5) in front of the TDW front. According to computations on physical and mathematical models of the CSD [4], this velocity is ensured by a pressure drop in the rarefaction wave behind the detonation front **BC**. This pressure is 2 or 3 times less than the mean pressure in the combustor. Since the mean pressure in the combustor is $p_{c1} \approx 1\cdot10^5$ Pa, the pressure before of **BC** front in not more than $0.5\cdot10^5$ Pa. In this connection, in the regime of nonstationary self-oscillatory oxygen ejection, the detonation wave behaves as a pump, and the rarefaction wave adjacent to the detonation front behaves as an inhausting piston. The detonation velocities in the PRC turned out to be less than those in the cylindrical combustor. This seems to be caused by the centrifugal forces acting on the detonation products reducing the pressure behind the front of the detonation wave **BC**.

4 Conclusions

Thus, regimes of continuous spin detonation of a hydrogen-oxygen mixture were obtained in a plane-radial combustor with an inner diameter of 100 mm and exhaustion toward the periphery including in the oxygen ejection mode. Upon the forced flow of oxygen first discovered the continuous multifront detonation. The structure of detonation waves was considered. For continuous spin detonation, the transverse detonation waves and the flow in the vicinity of these waves in the PRC plane were reconstructed. It was demonstrated that the detonation wave is significantly curved owing to the increase in the tangential component of velocity along the combustor radius. It was found that the scale effect is manifested only in terms of the number of rotating waves. However, the velocity of these waves increases with an increase in the PRC size because of the smaller influence of centrifugal forces acting on the products and reducing the pressure behind the detonation front. The mechanism of oxygen absorption in the mode of its ejection is revealed.

Acknowledgements

This work was supported by the Russian Foundation for Basic Research (Grant No. 18-41-540001r_a).

References

[1] Voitsekhovskii BV. (1959). Steady Detonation, Dokl. Akad. Nauk SSSR. Vol. 129, No. 6, 1254.

[2] Bykovskii FA, Vasil'ev AA, Vedernikov EF, Mitrofanov VV. (1994). Explosive combustion of a gas mixture in radial annular chambers. Comb., Expl., and Shock Waves. 4: 510.

[3] Bykovskii FA, Zhdan SA, Vedernikov EF, Samsonov AN, Misovets OV. (2014). Continuous detonation of a hydrogen-oxygen mixture in a plane-radial combustor with exhaustion toward the periphery. XXXI Siberian thermophysical workshop. November 17-19. Novosibirsk. Russia. 173.

[4] Bykovskii FA, Zhdan SA. (2013). Continuous spin detonation (Novosibirsk: Izd. Sib. Otd. Ross. Akad. Nauk) (ISBN 978-5-94671-011-4).

[5] Higashi J, Ishiyama C, Nakagami S, et. al. (2017). Experimental study of disk-shaped rotating detonation turbine engine. 55-th AIAA Aerospace Sciences Meeting. //doi.org/10.2514/6.2017-1286.

[6] Bykovskii FA, Zhdan SA, Vedernikov EF. (2010). Continuous Detonation in the Regime of Self-Oscillatory Ejection of the Oxidizer 1. Oxygen as an Oxidizer. Comb.,Expl., and Shock Waves. 3: 331.

[7] Bykovskii FA, Zhdan SA, Vedernikov EF. (2011). Continuous Detonation in the Regime of Self-Oscillatory Ejection of the Oxidizer 2. Air as an Oxidizer. Combust., Expl., Shock Waves 2: 217.

[8] Vasil'ev AA, Mitrofanov VV, Topchiyan M.E. (1987). Detonation waves in gases. Comb., Expl., and Shock Waves. 5: 605.