ROTATING DETONATION: HISTORY, RESULTS, PROBLEMS

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Starting from the initial period of investigations (about 140 years ago) the detonation wave (DW) was considered during long time as plane wave without any internal structure. It was great surprise when the unusual regimes of DW propagation in tube of round cross-section with spiral trajectory were observed by Campbell and Woodhead (1927). Such spiral trajectory on inner smoked wall was produced by an unknown element of DW-front. Moreover, the long luminosity front (tail) with strong pulsation was observed in detonation products. This regime was named as the spinning DW and for a long time it considered as exotic detonation regime. Later, the term of "transverse wave" (TW) was proposed by Voinov (1950) for unknown element of spinning configuration of DW-front. The structure of spinning DW (as in modern point of view) was solved firstly by Prof. B.Voitsekhovsky (1957). Prof. N.Manson (1946) was the first, who proposed the acoustic theory of spinning detonation. He assumed that the TW rotation is connected with acoustic vibration of detonation products. For spinning DW with single TW, its axial velocity $D_{\perp}^{S} = 1{,}84 \cdot c$, where c is the sound speed in detonation products, and 1.84 is the value of basic root of the Bessel function of the first order, which describes the radial component of velocity potential of a gas products for 2D acoustic equation. The time of one revolution of TW is $t^{0} = \pi \cdot d / D_{\perp}^{S}$, d is the tube diameter. The trajectory of spinning TW represents a spiral line with the step $\lambda = D_{II} \cdot t^{0} \cong \pi d$ and with the slope to the tube axis $tg \cdot \varphi_S = D_{\perp}^{S} / D_{II} = 1{,}84 \cdot c / D_{II} \cong 1,$ i.e. $\varphi_S \approx 45^{o}$, since $c / D_{II} \cong 0{,}55$, $D_{\|}$ is the longitudinal (along the tube axis) velocity of DW. Spinning DW in round tube is the unique stationary process of wave propagation with single transverse wave on the DW-front, which axially rotates along internal surface of tube wall.

The increased interest to use of a detonation process in various technological devices (the concept of detonation engine (DE)) was stipulated by the conclusion of the classical one-dimensional theory that the regime of the ideal Chapman-Jouguet DW is characterized by minimum growth of an entropy ΔS_D=min. The higher losses are inherent for combustion modes (laminar and turbulent) on a comparison with the C-J detonation mode. The idea to burn mixture in detonation mode appears many years ago. In latest years many investigators from different countries are connected with problem of pulse detonation engine (PDE), when DW as cyclical process propagates along the tube. Prof. B.Voitsekhovsky was the first who proposed to burn the mixture in detonation mode with the help of rotating waves, likely transverse wave of spinning configuration (Voitsekhovsky et al. 1963). Two schema were investigated more carefully for stabilization of rotating wave, located in some plane: a) the mixture components can be injected along the axis; b) injection in radial direction (from centre to outside or from outside to center). The detonation mode of mixture burning with the help of stationary rotating detonation waves was investigated effectively in Lavrentyev Institute up to now (Zhdan and Bykovsky 2006,2013). At latest years this problem was investigated experimentally by many investigators in different countries. Prof. Piotr Wolanski is the pioneer of investigations of rotating detonation in Poland and remarkable popularize of detonation engine in another countries. The space structure of spinning DW, especial near the tube axis, was analyzed numerically (Tsuboi and Hayashi 2006, Khasainov a.o. 2008, Manuilovich a.o. 2013, Aksenov a.o. 2013, ICDERS-2013-2019,…).

In given paper the schema of circle channel of inner radius R1 and outer radius R2 with radial injection of mixture from the centre was used for mixture burning in circle channel by the wave, rotated axially along the channel. Some important aspects of rotated DW were analyzed in this report: the velocities and pressure profiles of rotating waves, velocity deficit and energy-release; multifront system of rotated TWs; correlation of rotation velocity of TW with acoustic characteristics of reaction products; streak-records trajectory of rotated TW on moving film…The high velocity camera for streak-record registration of self-luminosity of rotating waves was used in experiments. The silphon gauge was used for measurement of static pressured in moved injected mixture. The special piezoelectric gauges with thermal shield were constructed for measurement of dynamic pressure profiles in rotating waves, at long duration (up to 5 seconds) of influence of hot products. The micro-thermocouple was used for measurement of average temperature in different points of combustion chamber.

On Fig.1 the process of initiation and initial stage of formation of rotating TWs is illustrated as streak-record of circle channel on moving film. It must be mentioned especially that it seems easy to produce the rotated TWs propagated with the velocity of ideal C-J detonation D_0, but as a rule the velocity of rotated wave D is less D_0 and D-value is closed to value of sound speed of detonation products c (usually $c \approx 0.55D_0$). Experimental values are equal $D_3 \approx 900$ m/s and $D_4 \approx 800$ m/s.

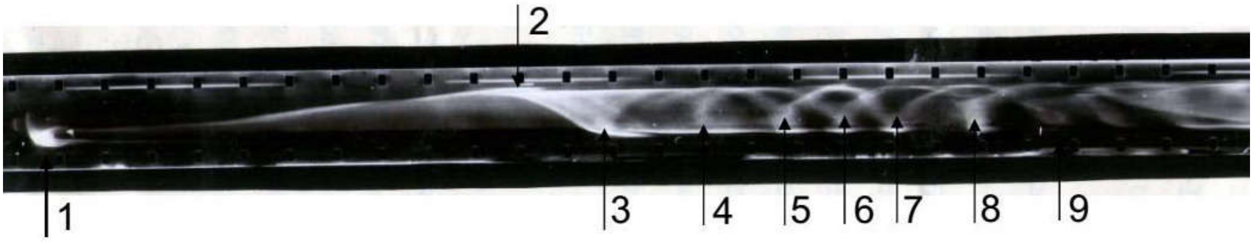
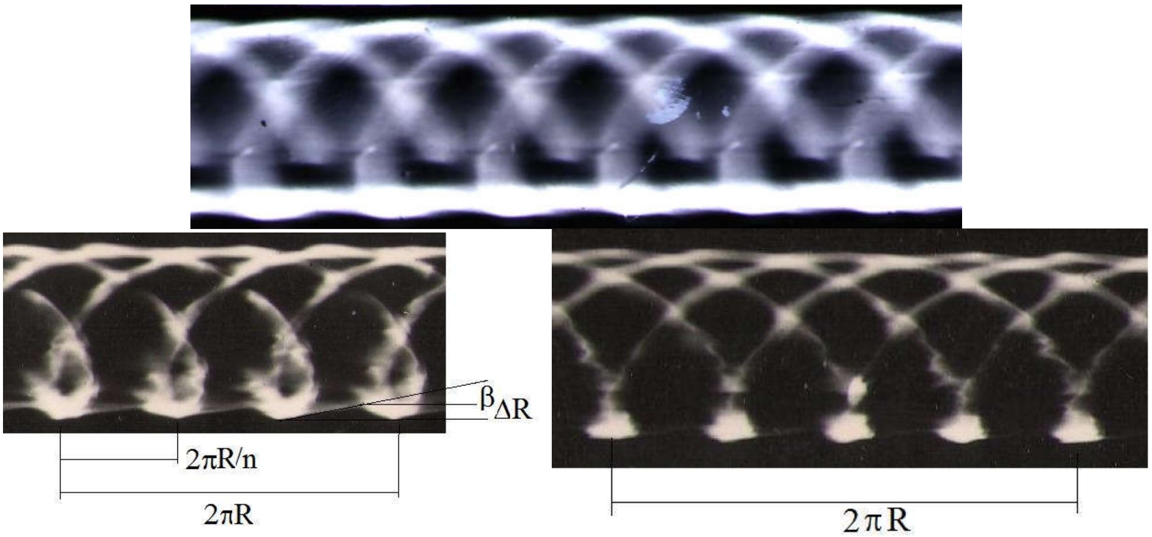


Fig.1. The initial stage of formation of rotating waves (upper photo) and the trajectories of rotating waves at quasi-steady regimes with 2, 3 and 4 TWs on total channel length 2πR of combustion chamber (lower).



The pressure profiles without abrupt sectors of front indicate also on acoustic character of influence of hot reaction products on velocity of rotating waves (Fig.2). Only the rare oscillograms with sharp front were detected by piezoelectric gauge, located near the bright peak of reaction zone of luminosity of rotating wave.

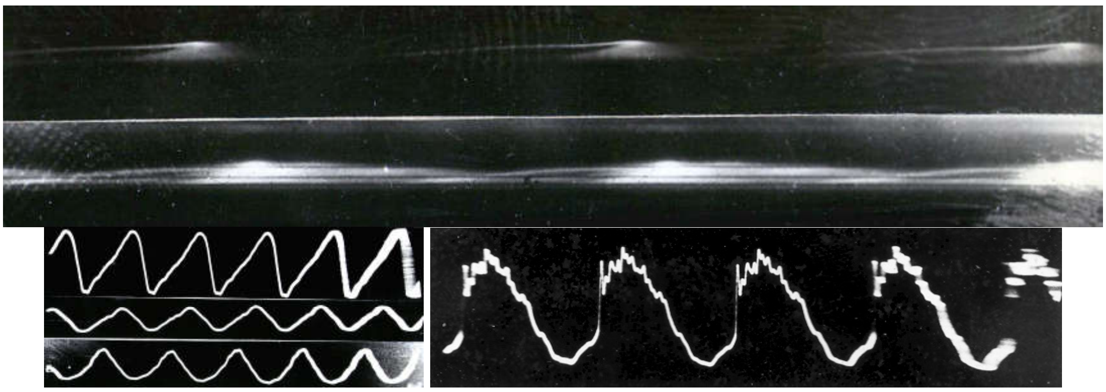


Fig.2. The luminosity photo of rotating waves (the regime of compensated velocity of wave velocity and film velocity) – upper photo, and similar photo with parallel lines which indicate the location of piezoelectric gauges on radius of combustion channel – next photo. The typical oscillogramms of pressure profiles in rotating waves are visible on lower photo – similar to acoustic wave (left) and similar to shock wave (right).

Some other aspects of rotating waves and problems of rotating detonation are discussed in given report.