# Spinning Detonation. History, Phenomenon, Possible Applications.

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In the last year 80 years have passed since the day of the phenomenon of spinning detonation detection by C.Campbell and D.W.Woodhead. This January (2007) academician B.V.Voitsekhovskii would be 85 years of age. In February 2007, exactly 50 years ago, his paper named "About Spinning Detonation", in which the idea of the transversal wave has been suggested for the first time, was published. This conception, developed by other authors too, has changed the general ideas about a front structure and has become the background for all following investigations of the detonation in gases.

In connection with these three anniversaries it is appropriate to recall events associated with investigations of spinning detonation of those years. Author of offered report in 1956-1959 have been the first student of both professor B.V.Voitsekhovskii and professor R.I.Soloukhin, he is the last living eye-witness and the first-hand participant of those events…

The phenomenon of the "spinning" detonation has been discovered by C.Campbell and D.W.Woodhead (1926-1928). Their first investigations have revealed a number of interesting features of the new phenomenon. If the mixture of carbon monoxide with oxygen detonates the formation of a brightly shining zone ("head") describing helical trajectory is observed near the wall of circular tube. The ratio of pitch of helix described by "head" to the tube diameter appears to be equal about 3.

With the help of photograph record through the transversal slit Campbell and co-workers have fixed a long shining strip – "tail" which follows to head. The frequency of "tail" rotation depended of the tube diameter. Insertion of the concentric bar changes frequency but did not change noticeably the longitudinal detonation velocity. N.Manson (1946) has given the explanation of this remarkable feature. Supposing that the tail is the transversal acoustic wave of natural oscillations of gas behind detonation wave, he has obtained the good coincidence the theory with experimental data. Later Fay (1952) has proposed the analogous theory. In the works of Chu Boa-Teh (1956), Soloukhin and Topchiyan (1959) the acoustic theory of tail received further confirmation and development.

The investigations of Bone, Fraser and Wheeler (1931, 1955) have supported the existence of the rotating zone. When the detonation passes from the tube of lead to glass one the spiral imprint has revealed on the inside wall of the second tube.

Initially it was assumed that the explosive mixtures fall into two "spinning" and "non-spinning" groups, but the investigations of Rivin and Sokolik (1936), Rakipova, Troshin and Shchelkin (1947, 1957), Mooradian, Gordon and Harper (1950, 1951) and many others authors have showed that the "spin" is observed in circular tube always when detonation propagates in marginal, limiting conditions, independently of ways of approach to the limits.

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Mooradian and co-workers also have revealed that out of limits overdriven detonations fail through spinning regime.

Already in experiments of Bone with colleagues it was revealed that sometimes the spinning detonation changes the rotation frequency by integer times. This phenomenon was named "multi-headed" spin.

Attempts to explain the phenomenon of the spinning detonation have begun since the moment of its discovery, but initial hypothesis of Campbell with co-workers about rotation of the overall mass of gas have been refuted quickly. Already Bone and co-workers have revealed that spin exists in the tubes of rectangle and triangle cross-section. Insertion into tube of inside diameter of 12 mm the longitudinal rib height of 1 mm did not affect the spinning detonation process. Perhaps they were nearer all to the truth by assuming that the ignition zone moves forward as sharp edge describing spiral trajectory. True, the physical sense of this effect remained not clear.

In 1945 Shchelkin proposed the first gasdynamic model of spinning detonation. He suggested that a break moving stationary in transversal direction arises in the shock wave igniting gas. Due to the composition of motions the normal to shock component of gas velocity increases about 1.4 times. Accordingly the temperature behind the shock rises approximately by a factor two. This lead to sharp decrease of the ignition delays and the gas burns practically immediately after the shock wave, and flame adjoins shock wave directly. The theoretical substantiation of Shchekin's model and calculations of flows were made by Zel'dovich and Brodskii (1946, 1950). In these calculations the angle of spiral was obtained equal to 44° that is near to the value given by experiment.

The shocks configuration like that has drawbacks. It is not clear, how manner the break constant size does support? What the reason does split up the primary shock? This configuration had no any sufficient experimental confirmation. For these reasons in the middle of 50-th academician Lavrent'ev attracted attention of Voitsekhovskii to the spinning detonation problem.

Above all it was necessary to receive the clear undistorted image of spinning head. The use of framing camera was impossible because of relatively low phenomenon luminosity and necessity of the very short exposure time (the full velocity of head movement is order 2 km/s). Troshin and Shchelkin (1949) have attempted to interpret the picture by applying sweeping camera with axial sweep direction and compensation the axial component of the velocity of the head optical image. This layout of equipment did not allow obtaining the undistorted clear picture due to the fact that the transversal movement was not compensated.

The decisive step has been made by Voitsekhovskii (1957). His homemade sweeping camera based on electromotor from the vacuum cleaner has transparent drum and big lens aperture (1/1.5). He used non-tradition inclination angle between the axis detonation tube and the drum so that the value and direction of drum velocity have fully compensated the movement of the head optical image. This allowed to widen the slit through that photographing was made and to have the equivalent exposure time more than by an order greater. As a result Voitsekhovskii has obtained the clear undistorted periodical photographs of spinning head, which served the basis of the new spinning head model with the transversal wave.

When shock wave propagates in gas with the Chapman-Jouguet velocity due to a great ignition delay, a layer of heated but unburned gas forms between primary shock and the flame

front. In this unstable layer growth of random disturbances leads to generation of detonation wave moving along the primary front across the gas fluxing out of shock. This transversal detonation wave burns up the gas after double compression. Therefore the ignition delay becomes negligible and the pressure exceeds the pressure behind the primary front about 8 times.

Scattering of the transversal detonation wave products causes the break of the primary front; the temperature behind it increases approximately by a factor two. The ignition delay becomes negligible and flame front coincides with disturbed shock front forming the overdriven detonation wave in this part of primary shock wave. This break is fixed in the self-luminosity photographs as the characteristic triangle projection. With moving off transversal wave its influence and temperature behind shock decrease, the flame front separates from the shock, which becomes invisible in the self-luminosity photograph, and the layer of unburned gas form. Through this layer transversal wave propagates. Thus the existence of break predicted by Shchelkin was confirmed, but it is not self-supporting formation and depends of scattering of the transversal detonation wave product.

Denisov and Troshin (1960) have received high quality smoke foil imprints of interaction of the spinning detonation and shock wave moving in the opposite direction. One can see in these imprints all elements of structure Voitsekhovskii's model but the picture compressed non-uniformly in axial direction in consequence of which was interpreted by authors incorrectly. The analogous experiments have carried out by Borisov and Kogarko (1959).

In the experiments of Voitsekhovskii primary front was fixed by indirect method without measurements angle between flow and shock. To calculate the full picture of flow near head it is need to know this angle and flow velocity. For this aim (1962) has obtained schlieren photographs of spinning detonation with help some modification of the full compensation method. In these pictures it was revealed that the conjugation of flows behind the primary shock and the transversal wave realizes with help of two triple points (intersections of tree shocks) and mentioned angle has been measured.

According to these data Mitrofanov and Topchiyan (1962) have calculated full picture of flows in the vicinity of the triple points. The calculated inclinations of shocks to the tube generatrix coincide with the experimental values in the limits of the measuring error. For the definitive conclusion about correctness of the model with the transversal wave Topchiyan (1962) and later more precisely Mitrofanov, Subbotin and Topchiyan (1964) have carried out investigations of the pressure field with conjugation of the pressure oscillograms to self-luminosity pictures. The ferroelectric ceramic pressure transducers have been manufactured with using special technology, and have had the acoustic wave-guide and sensitive surface diameter 1 mm and time resolution near to 0.7 microseconds. These investigations have completely confirmed the existence all elements of structure with transversal wave. The pressure values behind the all shocks in the limits of the measuring error (5-9%) have coincided with calculated one.

Shott (1964) has carried out wide investigations disposition of gasdynamic structures spinning detonation by various methods. Using schlieren photographing, smoke foil records, sensors of heat flux and electro conductivity he independently obtained the system of the

shocks and zones of chemical reaction coinciding completely with findings of Novosibirsk scientists.

The further detonation regimes from limits the conditions for ignition behind the primary shock are improved and the second transversal wave able to develop, but very rarely this second wave rotates in the same direction. That movement appeared to be unstable and more often two head rotating in opposite sense take place. With increase of the number of heads rotation becomes non essential at all and the detonation processes in gases are led by the transversal waves collisions as, par example, in the flat long rectangular channels in which one cross size is many times more than other.

The transversal wave turned out to be universal form inherent for all case of the gas detonation existence, except cases of strongly overdriven wave when detonation degenerates in shock wave. The transversal wave phenomenon suggests an idea to to burn gas mixture in the ring combustion chamber with the radial moving of combustible mixture and combustion products. The detonation wave moves perpendicular to main total motion of gas. The process, duration of which consisted off several second and confined only by the volume of stored mixture, was named “continuous detonation”. The last published by Voitsekhovskii (1959) results was received with use of premixed gas that supplied trough a narrow slit under lowered pressure in the ring volume. In the unpublished work Voitsekhovskii in the 1959-60 years have obtained continuous spinning detonation of the acetylene-oxygen mixed in ring combustion chamber under atmospheric pressure. In these experiments he detected the sharp decrease of heat flux to the walls of combustion chamber when continuous detonation is realized than with usual burning of the same mixtures.

Mikhailov and Topchiyan (1965) have obtained the photographs of self-luminosity of continuous detonation ringing heads and measured pressure profile in transversal waves. Continuous detonation of ethylene with oxygen in tubular annular slot was obtained by Edwards (1976). But the principal results in study of the continuous spinning detonation were obtained in investigations performing by Bykovskii, Mitrofanov, Zhdan and others from 1975 up to present day in the Lavrentyev Institute of Hydrodynamics.

In these works regimes of controlled continuous spinning detonation of various fuel in rocket and ramjet type combustor, with feeding of process by various forms of fuel (gaseous, two-phase and liquid) were obtained and extensively considered both experimentally and theoretically. Investigations performed in rocket-type combustor show that almost all gaseous or liquid hydrocarbon fuels mixed with air and gaseous or liquid oxygen can be burned in regime of continuous spinning detonation. It has been shown experimentally, theoretically and in numeric computation the possibility of transonic transition of the flow in continuous detonation. In the ramjet type of combustor experiments also show that it possible to burn fuel oxygen and fuel air mixture in regime of continuous spinning detonation.

The interest to this problem is associated with the possibility to use this phenomenon for stabilization and intensification of the combustion processes in various cases including rocket motors, sub- and supersonic air-breathing engines and others devices utilizing intensive burning of fuels.

It is known that combustion in the rocket motors is unstable and there is no possibility to try out the burning with engine of little scale and to transfer the results to natural scale. With appearance of such a stabile factor as velocity of the detonation process possibility of modeling increases. Detonation processes possesses the speed of burning wave several times

more than speed of turbulent flame by that the possibility of intensification of burning and retention of flame in various devices defines.