

Limiting Regimes of Wave Propagation in Active Mixtures

Anatoly A. Vasil'ev¹

¹Lavrentyev Institute of Hydrodynamics, SB RAS,
630090 Novosibirsk, Russia

1 Historical reference

The I-ICOGERS was carried out 40 years ago and Professor N.Manson was among the first organizers of this important International Meetings (together with Professors A.Oppenheim, R.Soloukhin, H.Wagner, a.o.).

Burning phenomena are known millions years, but gaseous detonation – only about 125 years. After its discovery the detonation wave (DW) was considered during long time as plane wave without any internal structure. It was great surprise about 80 years ago when the spinning regime of DW propagation in glass round tube was observed. Spinning DW considered for a long time as exotic detonation regime. Now it can be seems strange enough but the widely used term of “transverse wave” (TW) appeared about 60 years ago. About 50 years ago it was established that the transverse wave is the main element of spinning DW. Moreover, only 50 years ago the multifront structure of detonation front in gaseous mixtures was established in contrast to idealized one-dimensional (plane) schema. And now it is well known that the transverse waves play the important role and in multifront detonation.

The limiting supersonic regimes are the main object of my presentation. Such regimes were investigated by Prof. Manson, especially - spinning and galloping detonation. Correlation of cell size with size of equipment for different modes will be discussed also.

2 Typical regimes of wave propagation. Multifront DW

There are known the next regimes of wave propagation in combustible mixtures:

a) multifront detonation; b) spinning detonation; c) marginal detonation; d) galloping detonation; e) quasi-detonation; f) supersonic flame; g) subsonic (turbulent) flame; h) normal burning (laminar flame); i) flame quenching.

The gaseous self-sustaining DW has the periodically pulsating structure consisted elements of shock waves, induction zones, transverse waves, triple points, contact discontinuities, combustion zones, etc. The typical rhomboid imprint of multifront DW on soot surface (which produced by trajectories of TWs) is named as the detonation cell. At fixed diameter of detonation tube and parameters of investigated mixture the transverse cell size a increases usually with decrease of initial pressure P_0 . The cell size is the global geometric parameter of self-sustaining DW with pulsating front, because with its help the many important parameters can be estimated with sufficient accuracy, for example, critical initiation energies for different symmetries.

At conditions faraway limiting ones, as a rule, the velocity of self-sustaining multifront DW equals to Chapman-Jouguet value: $D_{mf}=D_0$.

The size of experimental equipment must exceeds the cell size more then one order for realization of self-sustaining regime, which must be independent on influence of any boundary perturbations: $d \gg a$.

3 DW with single transverse wave – spinning and marginal

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 structure of spinning DW (as in modern point of view) was deciphered firstly by Prof. B.Voitsekhovsky. His experimental photo of self-luminescence of spinning DW with bright transverse wave became classical.

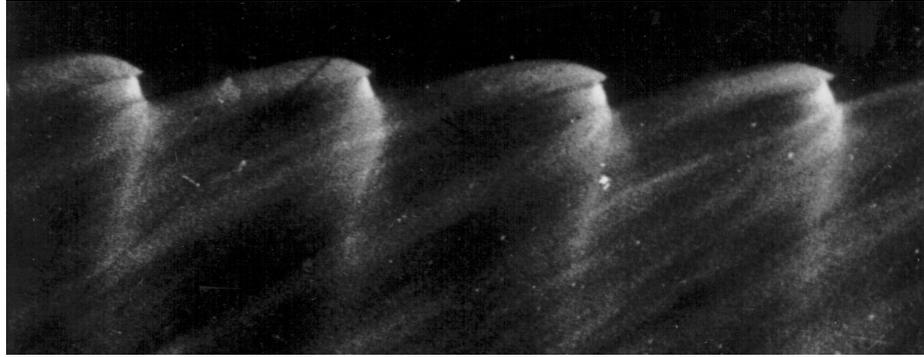


Fig.1. Self-luminescence of spinning DW in round tube.

Prof. N.Manson 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 major 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 $\lambda = D_{\parallel} \cdot t^0 \cong \pi d$ and with the slope to the tube axis $\text{tg} \cdot \varphi_s = D_{\perp}^S / D_{\parallel} = 1,84 \cdot c / D_{\parallel} \cong 1$, i.e. $\varphi_s \cong 45^\circ$, since $c / D_{\parallel} \cong 0,55$, D_{\parallel} is the longitudinal (along the tube axis) velocity of DW. At multifront DW-regime the transverse a and longitudinal b are the sizes of elementary cell, which are connected by the relation $a = b \text{tg} \varphi$.

The condition of spinning regime as the limiting regime of steady DW-propagation can be written as $a = \pi d_s$. So, if the dependence $a(P_0)$ for explosive mixture are known (for example, from calculation), then the diameter d_s for the limiting regime - spinning DW - may be determined according to last formula.

At experimental investigation the circular detonation tubes and the detonation channels of rectangular cross-section are widely used. The regime with single TW is the analog of spinning detonation in the circular tube, it was named a marginal one for rectangular channel. In this case the TW moves periodically between the lateral walls of rectangular channel. The spiral track of TW on the lateral surface of circular tube (which is typical for spinning detonation) is transformed into rhomboid imprint, typical for the cellular structure. The channel width l is connected with cell size for marginal regime by the relation $l = l_m = a/2$. According to the dependence $a(P_0)$ and last formula the width of rectangular channel l_m , where the marginal regime is achieved, may be determined.

However, last relation is not sufficient criterion for determination the limit of quasi-stationary propagation of gas detonation in rectangular channel, as far as the depth of channel δ is negligible in this formula.

Assuming the detonation limits to be determined by equal level of losses in the circular and rectangular channel, the relation of geometric parameters of the channel with physical-chemical parameters of explosive mixture may be estimated with the help of the hydraulic analogy. For the rectangular channel with the size $l \times \delta$ hydraulic diameter $d^o = 2l\delta / (l + \delta)$. The detonation limits will be described by relation: $d_s = d^o$, so $a/\pi = 2l\delta / (l + \delta)$.

Many aspects of near-limited regimes require the additional investigations. It is interesting to investigate how single TW “rotates” in channel of arbitrary cross-section (square, triangle, elliptic, ...)? For such channels the rotated modes in acoustic equation are absent, and TW must be reflected from each wall instead of “quasi-rotation”. Similar investigations for square channel clearly recognized the new peculiarities of DW propagation,

for example, the transgression of identity of TW movement along the different walls of square channel or the diagonal mode of pulsation of DW front without rotation.

Transverse wave of spinning configuration has two triple points in contact areas of TW with leading shock front and with the loop in detonation products. When the size of TW is great sufficiently, then the TW trajectory on smoke foil looks as double line. It is interesting, that in some mixtures the instability developed and on transverse wave. Such instability looks as cellular structure among double lines of TW trajectory with cell size much lower than the cell size of main structure. This phenomenon is known as "fine" structure of spinning DW. Recently the new type of cellular structure – "double" structure – was found in some mixtures, when the detonation cells of great and small scales are registered simultaneously on whole area of soot surface (not only in TW trace).

What is the space structure of spinning DW? This problem was carefully investigated experimentally by many investigators and at last time numerically.

The classical rhomboid cell structure appears in tube when two TW (as minimum) exit on detonation front and such TWs move in opposite direction and collide periodically (as in multifront DW). It is interesting, that although the regime with rotation of both TWs in one direction is possible theoretically, but it not observed experimentally, probably because of nonconservation of the moment of impulse? The idea to burn mixture in detonation mode appears many years ago. In latest years many investigators connected with problem of pulse detonation engine. The detonation mode of mixture burning with the help of stationary rotating detonation waves was realized firstly by Prof. B.Voitsekhovskiy about 50 years ago. The some peculiarities of stationary rotating detonation were investigated in my diploma dissertation. These regimes are investigated effectively in our Institute up to now. The engine with stationary rotating DW is alternative to pulse detonation engine.

For different mixtures the velocity of spinning DW $D_S=(0.8\div 1.0)D_0$.

It is marked especially, that the circle surface of tube wall provides the rotate motion of TW. In coaxial gap the spinning regime was observed also, but it velocity differ from value typical for tube. Will transverse wave rotates in gaseous gap without external rigid wall? Such schema of "external detonation" was investigated by author and it was established, that spinning regime (single TW on DW front) without support of external boundary is impossible. The circle gaseous layer can be burned by rotated DW, but this DW must be multiheaded. In longitudinal mixture jet (gaseous charge without concave wall) the spinning regime becomes impossible also: the limiting regime of DW propagation in free jet (without wall) is typical multifront regime.

5 Quasi-steady galloping DW

At further decreasing of initial mixture pressure P_0 lower than for spinning detonation the new regime – galloping DW – is observed with powerful longitudinal pulsations and averaged quasi-stationary velocity. Prof. N.Manson was among the first investigators, who studied carefully the galloping wave. During initial stage of each pulsation the strongly overdriven non-stationary DW is observed with very small-scale multiheaded structure, at



Fig.2. Galloping regime in flat channel (smoked imprint): DW propagates left to right.

next stage the wave decreases monotonically from multifront mode up to spinning mode. During the next stage the attenuating spinning wave destroy and transform to supersonic non-stationary complex from separated shock wave and flame front with increased distance among them (increased induction zone). Such complex propagates as long as the induction time τ of shock-compressed explosive mixture is finished (for regime in smooth tube, when reinitiation processes due to some external influences can be neglected). On final stage (when τ is finished) the new explosion centers appear in induction zone of such decelerated wave near the flame front, which produce the strong initiation of gaseous mixture in induction zone. The blast wave from such explosion creates the new high overdriven DW after overtaking of initial shock front. The processes are repeated during the next pulsation.

A spatial pitch of 1D oscillations attains hundreds of channel diameters. The average value of velocity oscillations is 10%–30% lower than the CJ detonation velocity $D_G=(0.7\div 0.85)D_0$ and remains constant.

The limiting criteria for galloping detonation may be formulated in the following form: $d_g \approx 2\lambda_{10}$.

6 Quasi-detonation

At further decreasing of initial pressure (lower than for galloping DW) the quasi-stationary combustion regime with high supersonic velocities (~ 1000 m/s) can be observed. As for high-velocity regimes of combustion ($D_F = 0.5 D_0$), they may be classified with quasi-stationary regimes similar to the multifront and galloping regimes of detonation and may pretend to be referred to the quasi-detonation regimes due to their supersonic nature and leading shock wave. For such regimes a low level of pulsations of flame front and full absence of cellular structure are typical. The formation of the wave structure of the low-velocity detonation is caused by transport processes near the flame surface. The flame is located at a distance of 3–8 channel diameters from the SW and has a shape of an almost flat disk in the flow core with an adjacent oblique flame in the boundary layer.

The limiting criteria for low-velocity detonation may be presented in the form: $d_{lv} \approx \lambda_{10}$.

7 Supersonic and subsonic turbulent and laminar flames

At further decreasing of initial pressure P_0 the combustion regime with supersonic and subsonic velocities are observed. For such regimes a full absence of cellular structure are typical also. The leading shock wave with sharp pressure increasing transforms to compression wave with smooth pressure profile. It is interesting to receive theoretically the criterion of steady propagation for such regimes.

8 Deficit of average velocity or pulsation scale?

The averaged velocity of the above mentioned processes can be the basic parameter for the classification of the limiting regimes, but the relation between the characteristic scale of pulsation and the detonation channel size is more preferential for this purpose. The multifront regime, being far from the limiting one, is characterized by the value $b/d \ll 1$; here the longitudinal size of cell b is naturally to be chosen as a pulsation scale. The spin step $\lambda \approx d$ may be chosen as a characteristic scale for spinning regime. Although the velocities of spinning and galloping regimes differ insufficiently, this difference is rather sufficient in pulsation scale - the duration of gallop pulsation is some tens of calibers.

9 Remark

50 years ago (in 1957) the Government of the Soviet Union took the decision about creation in Siberia of a new scientific center. Novosibirsk was chosen as the basic town for realization of this Project, later Novosibirsk was named as the Informal Capital of Siberia. Institute of Hydrodynamics (LIH) was the first Institute of Novosibirsk Scientific Center and in this June we celebrated the fiftieth jubilee. From the beginning of LIH history the problems of detonation and combustion were basic objects of investigation and Novosibirsk detonation school is well known among scientific community. And in conclusion I want to say also, that Prof. N.Manson visited the Novosibirsk Scientific Center and our Institute in 1969, when Novosibirsk was chosen as first Russian town for 2-nd ICDERS.