The Basic Results on Reinitiation Processes in Diffracting Multifront Detonations. Part I.

A.A. Vasil'ev[1]*, A.V. Trotsyuk[1], P.A. Fomin[1], V.A. Vasiliev[1], V.N. Rychkov[1], D.Desbordes[2], B.Khasainov[2], H.N.Presles[2], P.Vidal[2], P.Demontis[2] and C.Priault[2]

[1]M.Lavrent'ev Institute of Hydrodynamics, SB RAS, Novosibirsk, 630090 Russia

[2]Laboratory of Combustion and Detonation, ENSMA, BP 40109, 86961 Futuroscope, France

Abstract

The basic results of experimental investigations on reinitiation processes in diffracting multifront detonation wave (DW) are discussed in connection with problem of practical application of new ecological technology for worn-out tire destruction, where the cooled worn-out tire destroys with the help of gaseous detonation. The experimental results for various fuel-oxygen and fuel-air mixtures are presented at wide range of mixture compositions, initial pressure and temperature, geometrical sizes of experimental equipment, symmetry types, dilution of inert gases, *etc*. Classical and nontraditional schema of DW-diffraction are investigated, such as multipointed initiation, DW-excitation by circular charge, initiation space-oriented longitudinal charges, initiation by circular charge, diffraction on concave boundary, diffraction on contact surface of different mixtures, flame diffraction, *etc*. The main characteristic parameters are identified for each diffraction schema. The physical processes taking place directly in the DW-front plays the governing role in reinitiation. The most important among these processes are collisions of transverse waves, which stick out as microscopic initiators. The optimization problem of DW-initiation from spatial and temporary distribution of energy is discussed carefully. This data can be used at hazard estimation also.

Introduction

The new method of worn-out tire destruction [1] is based on drastic pressure increase at the explosion of detonable gas mixture inside the tire. It can provide a separation of rubber from metal cord with the small pieces. The pulse detonation device (PDD) for worn-out tire destruction (Fig. 1) consists of the detonation tube (3) connected to the tire destruction chamber (4), injection (2) and ignition (1) systems. A tire (5) is cooled down to a fragile state. At such PDD the DW-transition from tube to tire is typical diffraction process of multifront detonation.

Diffraction of multifront detonation (MFD) wave is a complex nonsteady gasdynamic phenomenon comprising destruction and recovering of the ordered structure of multifront DW, which arise at change of the geometric size of the gas charge. Previous investigations [2-6] revealed two qualitatively different propagation modes of DW-diffraction by a convex angle (expansion), depending on the ratio of charac-

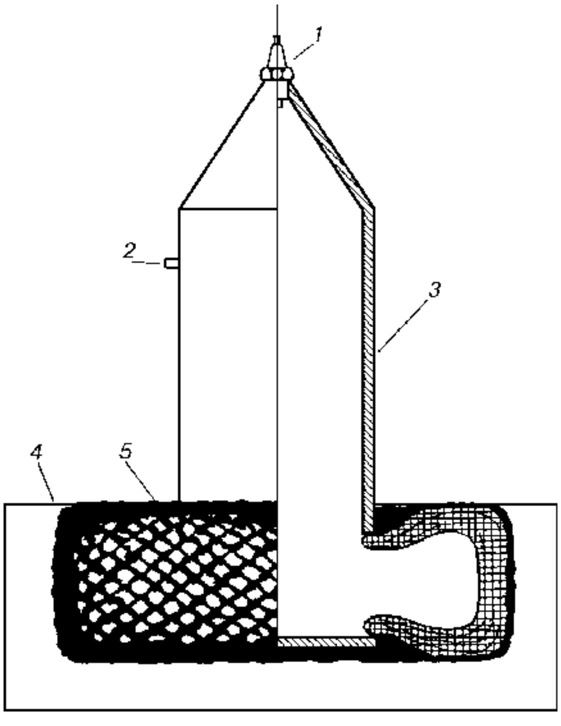

Fig. 1. Schema of PDD for utilization of worn-out tires

---

*corresponding author. E-mail: gasdet@hydro.nsc.ru teristic sizes of the initial charge (*e.g.*, its diameter *d*) and on the physicochemical parameters of the explosive mixture (cell size *a*). These modes are: *(i)* initially self-sustaining DW decays after beginning of interaction with the expansion angle and degenerates to form a nonsteady three-dimensional complex comprising an attenuating shock wave and trailing turbulent flame, and *(ii)* after interaction and a quasi steady transition period DW reinitiation is observed (Fig. 2).

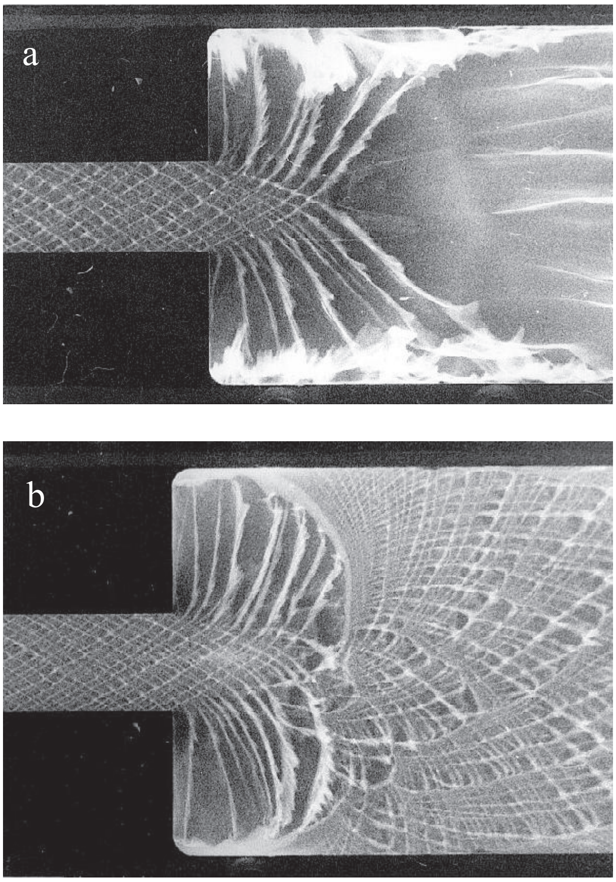

Fig. 2. Self-luminosity photographs of MFD-diffraction: a – DW-decay, b – reinitiation

Based on the first stage results of diffraction investigation the following relation was suggested:

$$d_{**} = 13a = \text{const} \qquad (1)$$

for estimating the critical diameter d_{**} of DW-transition from a channel to unconfined space, that is, such a diameter of the gas charge at which a self-sustaining DW exiting from a tube into an unconfined mixture volume (diffraction by angle $\alpha = 90°$) equiprobably decays or is transformed into a spherical detonation wave; *a* is the characteristic cell size of MFD.

Equation of type (1) was checked carefully in conjunction with hypothesis on the key role of the cellular front structure in DW-initiation and propagation and with the possibility of assessment through *a* of a great many critical parameters characterizing MFD, namely, the initiation energy for various flow symmetries, geometrical sizes critical for DW propagation and transformations in channels of different configurations, size of a projectile capable of detonation excitation in the mixture, critical sizes of unconfined gaseous charges, critical constants characterizing the induction period, and so on [7-16]. It was established that relation (1) could be used only for approximate estimation of critical diffraction diameter, d_{**}/a value for different mixtures is not constant and varies at least within a factor 2 [17].

Numerical modeling of DW-diffraction in the rigorous multidimensional formulation is an extremely complicated problem. Some Codes for DW-diffraction are known (for example, [18-20]), but the critical d_{**}/a value consisting with experimental data not calculated yet.

This work presents the basic results of experimental investigation of MFD-diffraction for various symmetries and fuel-oxygen and fuel-air mixtures (including diluted with inert gases).

Typical Schema of Experiments

When multifront DW propagates in a rectangular channel of small depth the luminosity of DW exhibits a characteristic rhomb-like pattern similar to smoked-foil prints. The two methods for recording detonation front cells (soot prints and luminosity) use the fact that the gas parameters behind transverse waves in DW are enhanced: the soot prints use high pressures in these zones and luminosity technique records high temperature zones. We emphasize that mixture burning shows no characteristic structure on a smoked foil or luminosity records, which enables one to simply and unequivocally discriminate between detonation and burning processes.

Fast shadowgraph framing photography (IAB-461 Schlieren apparatus in combination with SFR framing camera), soot-print technique, and open-shutter photography [5] were employed. The typical schema of experimental conditions of diffraction and reinitiation of spherical DW and optimization of this processes is illustrated on Fig. 3: diffraction at variation of expansion angle (with rectilinear $y = x\,\mathrm{tg}\alpha$ or curvilinear $y = f(x)$ boundary; diffraction of overdriven DW produced by flow compression in conical nozzle;

at transformation of symmetrical initiator for initiation of spherical DW up to linear initiator for initiation of cylindrical DW. Schema of spatially distributed ring or multi-pointed initiators and schema of DW-diffraction on boundary of different combustible mixtures were investigated also (Fig. 4).

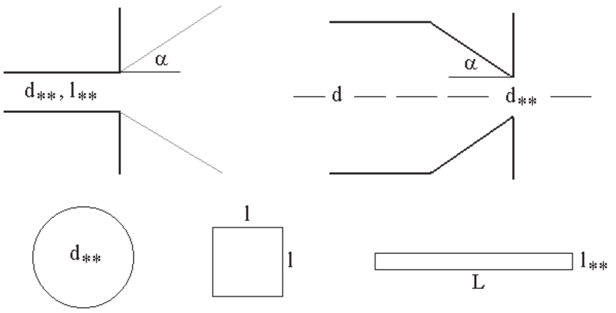

Fig. 3. Typical schema of experimental conditions on diffraction and reinitiation of spherical DW: d – tube diameter, d_{**} – critical diffraction diameter, l and L – sizes of rectangular initiator, α – diffraction angle

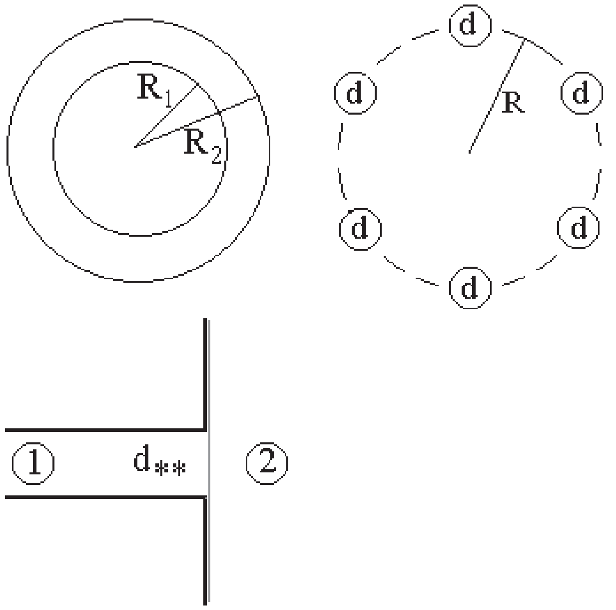

Fig. 4. Typical schema of experiments on diffracted initiation of spherical DW with help of ring (radius R_1 and R_2) or multi-pointed initiator (located on circle of radius R) – upper schema. Lower – schema of diffracted initiation on contact surface of different combustible mixtures (1 and 2).

The Main Experimental Results

The following schema were studied at $v = 3$ (index of spherical symmetry):

(a) Classical [2-4] diffraction at DW transition from a straight constant-diameter tube into a hemispherical mixture volume – $\alpha = 90°$ (vessel of much larger cross section in compare with tube; it is axial-symmetry initiator likely equivalent charge for half-space in the form of a flat disc). On Fig. 5 the dependences of critical diffraction diameter (mm) on initial mixture pressure (atm) for typical fuel-oxygen mixtures are illustrated. Such dependences are similar also for fuel-air mixtures (Fig. 6).

It has been found out at comparison of the $d_{**}(P_0)$ dependence (diffraction angle $\alpha = 90°$, $d = 2\text{-}80$ mm) that the critical reinitiation mode is observed at the same pressure P_* of the mixture when both the classical (initiator tube (IT) of constant-diameter (d_{**})) schema and its modification (IT of a larger diameter $d_0 > d_{**}$ and thin metal diaphragms with an axial orifice of diameter d_{**} at the exit plane) were used. This means that the physical processes taking place at the DW front play the governing role in reinitiation. The most important of these processes are collisions of the transverse waves, which are likely as microscopic reaction initiators.

The governing parameters of $\alpha = 90°$ schema are the critical diameter of detonation reinitiation d_{**} and cell size a.

(b) *Reinitiation at various diffraction angles*

As the diffraction angle α varies (transition of the initiating DW from IT into volume through divergent cone, $\alpha = 0\text{-}90°$, $d = 8\text{-}40$ mm), the detonation-failure phenomena in diffracting DW are enhanced with increasing α until a certain limiting value α_* is attained (*e.g.*, for $C_2H_2 + 2.5O_2$ mixture $\alpha_* \approx 30°$ at $v = 3$ and $\alpha_* \approx 45°$ at $\nu = 2$); at $\alpha \geq \alpha_*$ the failure phenomena are virtually independent of the cone divergence angle – Fig. 7. At the same time, diffracting wave is very sensitive to artificial reinitiation, *e.g.*, due to interaction of the wave with various "obstacles" of the experimental equipment (gaps, crevices, screw heads, steps, *etc.*). Induced reinitiation leads to reduction of the critical diffraction parameters.

Experimental modeling of DW-transition from a narrow tube of diameter d_1 into a wider one d_2 have shown that for correct determination of d_{**} (or l_{**} at $v = 2$) one should satisfy the following condition $d_2 \geq 5d_1$, the governing parameters in this case are d_{**}, a, and α. At lower d_2 the reinitiation occurs due to wave reflection from the walls being the more efficient, the higher the d_1/d_2 ratio ($d_1 = 5\text{-}60$ mm and d_2 varied up to 250 mm). That is, the d_1/d_2 ratio must be added to the above governing parameters under these conditions.

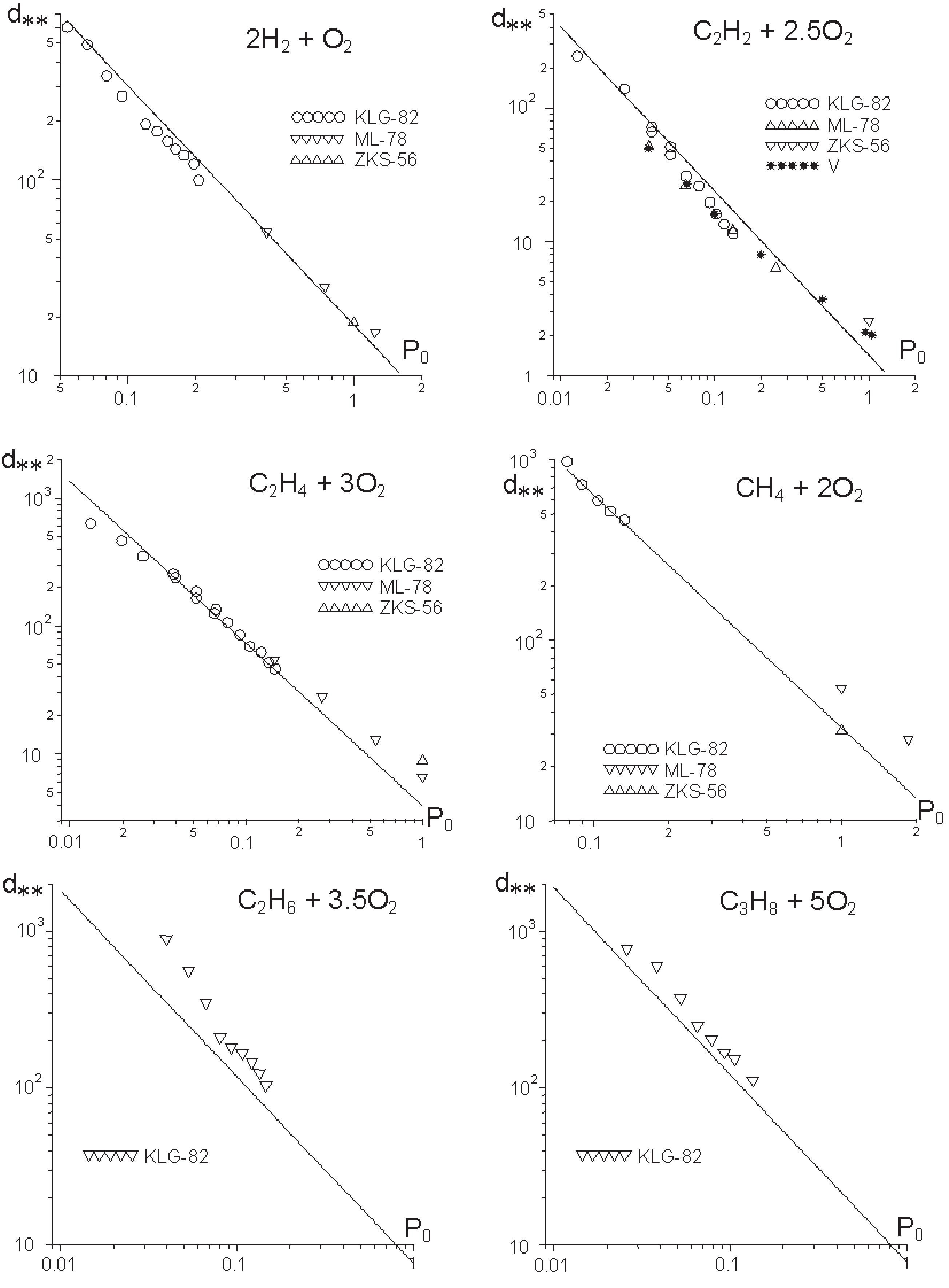

Fig. 5. Critical diffraction diameter (mm) on initial pressure P_0 (atm) for stoichiometric fuel-oxygen mixtures

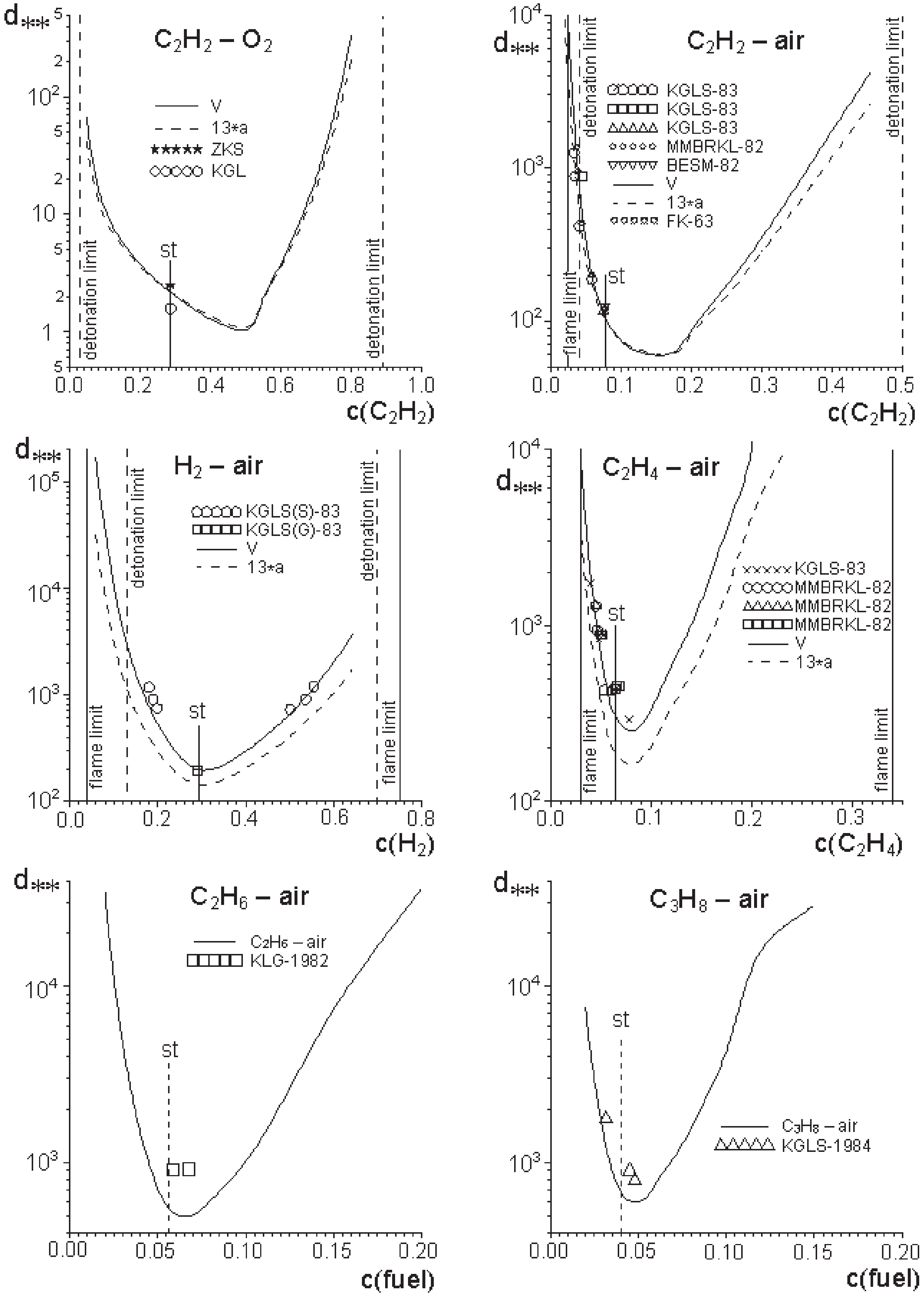

Fig. 6. Critical diffraction diameter (mm) on molar fuel concentration

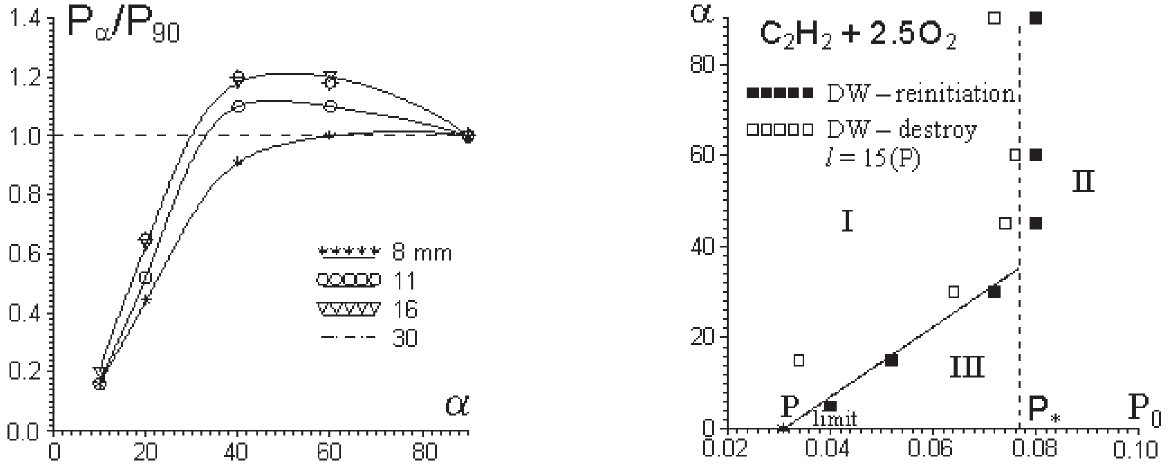

Fig. 7. Dimensionless critical pressure (divided on critical pressure at α=90°) on diffraction angle for spherical initiation (left). Critical initial pressure P_0 (atm) on diffraction angle for cylindrical initiation (right)

(c) *Reinitiation of overdriven multifront DW*

As established in investigations of MDW diffraction in a converging cone (the wave was overdriven in a cone with angle α at constant entrance *(d* = 100 mm) and variable exit *(d* = 8-20 mm) diameters with subsequent abrupt expansion of the DW (transition to unconfined mixture volume), the governing parameters are α and exit diameter d_{**} (or the overdrive amount): at a fixed d_{**} and variable α the efficiency of reinitiation by overdriven waves is the highest at $\alpha \approx 20°$ and does not differ from that observed in experiments with self-sustained DW at $\alpha \approx 0^o$ and $\alpha \geq 60°$ - see Fig. 8 (its dependence on cross section areas at the cone entrance and exit being weak). The criterial reinitiation parameter d_{**}/a in experiments with overdriven DW differs from its counterpart for self-sustained DW at small overdrive amounts β (the velocity ratio) by no more than 10%, as β increases further, $d_{**}la$ rises appreciably – Fig. 9.

(d) Asymmetric initiation (equivalent plane charges in the form of an ellipse, square, triangle, and rectangle), the governing parameters are the small and large ellipse semiaxes, side of a regular triangle, length *L* and width *l* of a rectangular charge [21-25]. For this case the effective critical diameter was defined as $d_{**} = \sqrt{d_1 \cdot d_2}$. The results of experiments are presented on Fig. 10.

Transformation of the charge shape from a circle to rectangle with $k = Lll >> 1$ (schema on Fig. 4) allows one to change continuously the spherical initiation to cylindrical one (results - see Fig. 11) and to assess the ratio between the characteristic sizes d_{**} for the spherical and l_{**} for the cylindrical symmetry [16].

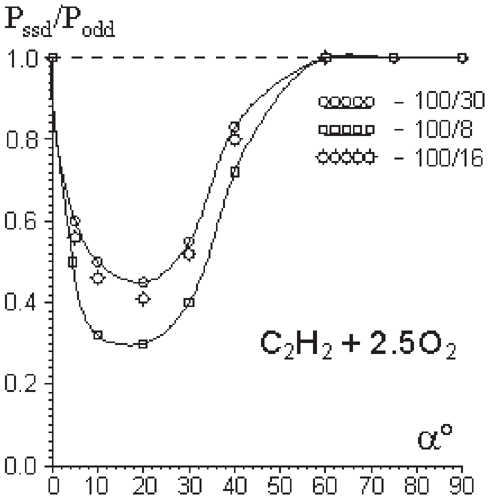

Fig. 8. Dimensionless critical pressure (Self-Sustaining Detonation (ssd) and Over-Driven Detonation (odd) on diffraction angle

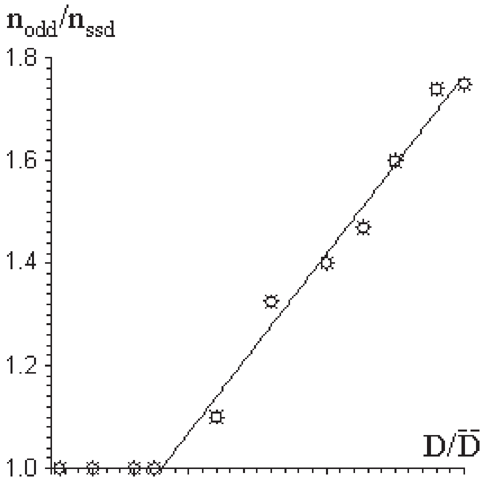

Fig. 9. Dimensionless cell numbers for initiation of spherical DW on over-driven ratio of DW-velocity

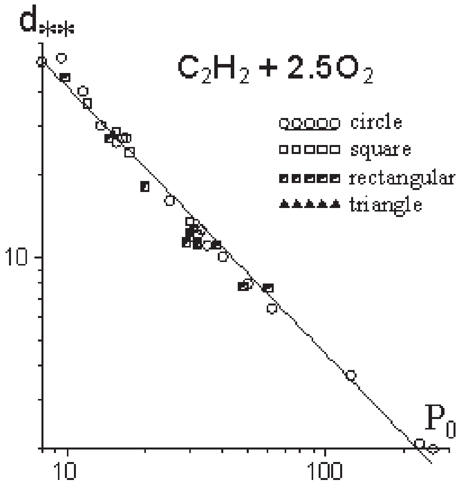

Fig. 10. Equivalent critical diameter for spherical initiation on critical pressure (different shape of initiator)

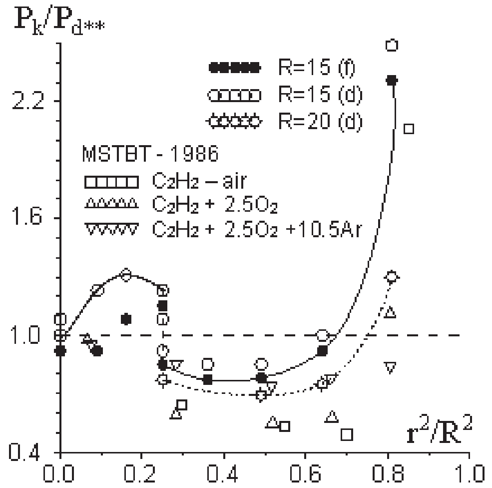

Fig. 11. Critical pressure of reinitiation of spherical DW by ring initiator (divided on critical pressure at $R_1=0$ and $d_{**}=2R_2$) on ratio of inner ($r = R_1$) and outer ($R = R_2$) radius

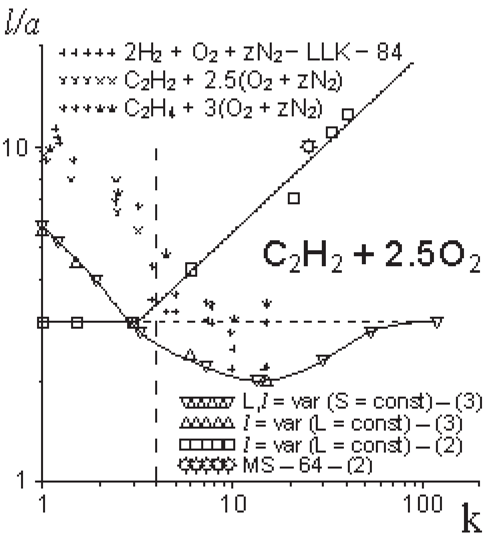

Fig. 12. Critical diffraction ratio for initiation of cylindrical DW on degree of transformation of initiator (from square form to rectangular)

(e) Ring initiator, the governing parameters are radii R_1 (inner) and R_2 (outer) of the charge and a [26-28]. There is an optimal ratio between R_1, R_2, and a at which the efficiency of ring reinitiation is about an order of magnitude higher than in runs with a full circle (see the areas below dotted horizontal line on Figs. 11-12).

(f) Multiple spot reinitiation scheme, the governing parameters are the number of individual microscopic initiators n of a representative size d and of their spatial orientation with respect to each other [29]. The results and conclusions are similar to those in paragraph **(e)**.

(g) Combined diffraction version, when the plane of the sudden change in the tube section is at the same time an interface between explosive mixtures of different activity [29].

The chemical composition effect, when DW goes from one gaseous mixture into another, is often used in practice at determination of the concentration limits of gaseous detonations (a steady DW enters the tested mixture and then either is transformed into DW inherent in the new mixture or decays). A certain volume of a chemically active mixture can be used as an initiator for normally detonating mixtures. Typical situations are the next: 1) direct contact between reacting gases; 2) gases are separated by a layer of an inert gas. The latter case is similar to the well-known gap test for solid explosives.

Mixtures significantly differing in their reactivity, $2H_2 + O_2$ and $C_2H_2 + 2.5O_2$ in various combinations were investigated. The experimental results support the idea that collisions of transverse waves play a key role in reinitiation of multifront detonations (Fig. 13).

At $\nu = 2$ (cylindrical symmetry) the following situations were explored:

(1) Diffraction of DW when it enters from a tube into a gap between flat discs at the center of one of them and spreads there in the form of a diverging quasi-cylindrical DW, the governing parameters are the initiator tube diameter d_{**}, the gap thickness Δz, and cell size a.

(2) Reinitiation of DW when it passes from a narrow channel into a wide one (at a constant depth), the governing parameters are the width $\Delta y \equiv l$ and height Δx of the initiator (narrow) channel, and diffraction

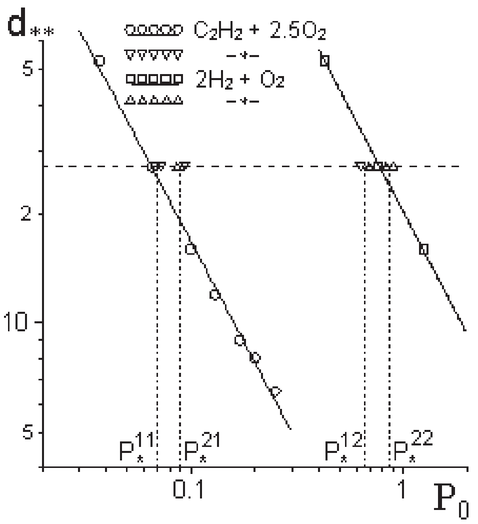

Fig. 13. Critical diffraction diameter on initial pressure for case of fiffraction phenomena on contact surface of different mixtures

angle α.

Investigations of diffraction of DW passing from a narrow channel to a wider one ($\nu = 2$) [28-31] have demonstrated that the critical reinitiation modes depend on the two sizes of the initiator (narrow) channel – width $\Delta y \equiv l_{**}$ and height Δx (the experimental range of Δx and Δy is 2-30 mm) – schema of experiments and results are presented on Fig. 14. This result differs significantly from the conclusions drawn in [32,14] according to which the criterial reinitiation parameter for cylindric waves $l_{**}/a \equiv 10$ for various mixtures and experimental conditions. The effect of Δx vanishes at $\Delta x/l \approx 1$, that is, for MFD-experiments with a square (or elongated along the x axis) section of the initiator channel with a minimum l_{**}/a value correspond to the strictly cylindrical diffraction pattern (*i.e.* the flow pattern is independent of the charge height). As $\Delta x/l \to 0$, parameter l_{**}/a increases, this increase is most prominent at $\Delta x < a$.

(3). Diffraction by a curvilinear surface, the governing parameters are the width $\Delta y \equiv l_{**}$ and height Δx of the imitator (narrow) channel and also the $y = y(x)$ dependence for the curvilinear generatrix of the boundary perturbation. Self-luminosity photographs of MFD-diffraction with destruction and reinitiation are demonstrated on Fig. 15. Points **A** mark the reinitiation centers in expanding wave. For circle sector boundary the radius R become the governing parameter instead of the $y = y(x)$ dependence. The results of investigations are presented on Fig. 16.

At plane initiation ($\nu = 1$) the experimental setup is a constant-section tube or channel, the governing parameter is the length Δz_{**} of the zone occupied by the initiator gas.

Investigations revealed independence of the process of MFD-reinitiation from the initial pressure of the mixture when the zone of initiator gas exceeds the von Neumann spike length (at a given P_0) – Fig. 17. The dependence shows up when part of the frontal DW zone efficiently contributing to initiation is "consumed" [33].

The Effect of Inert Diluent

Diffraction experiments with various mixtures di-

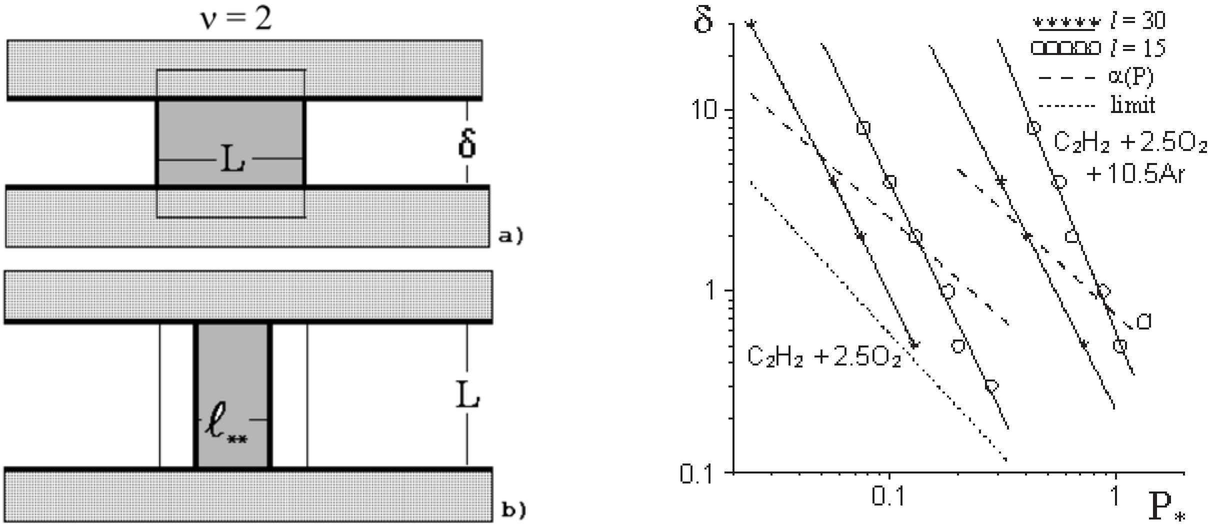

Fig. 14. Schema of diffraction investigation of cylindrical DW and experimental data of critical channel depth: a) at variation of depth δ (mm) at channel width L = const; b) at constant channel depth by variation of its width. Critical depth on initial pressure – right graph

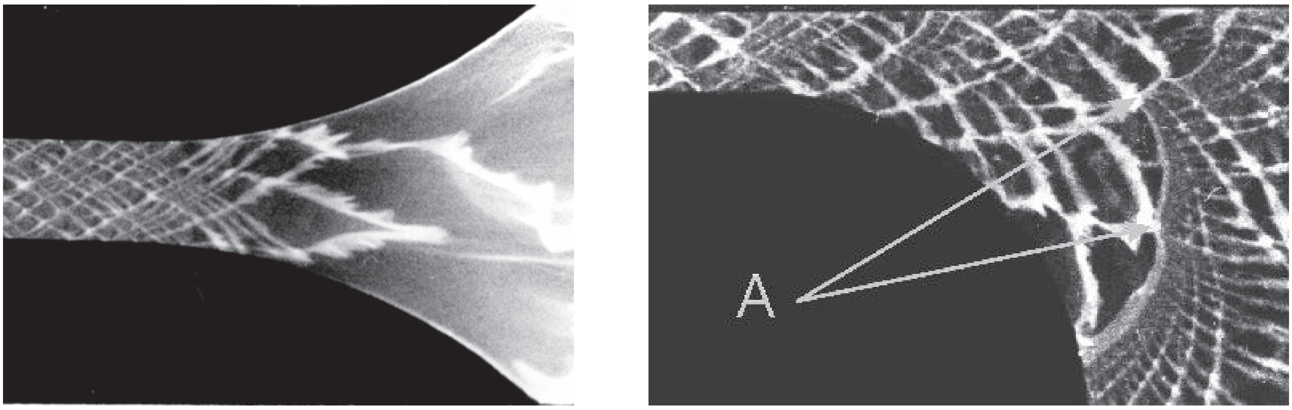

Fig. 15. Self-luminosity photographs of DW-diffraction on concave surface: left – decay; right – reinitiation in A-points

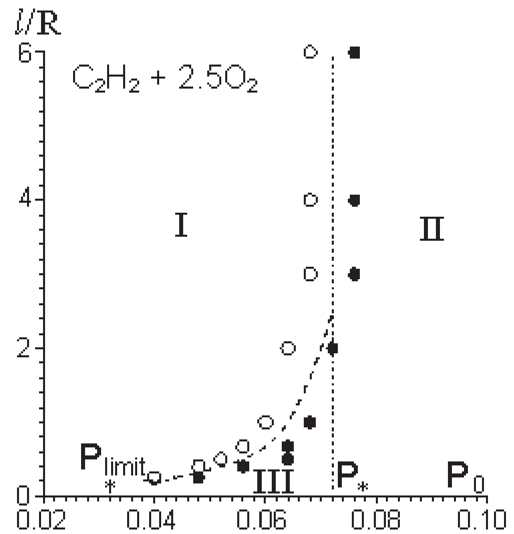

Fig. 16. Critical conditions of DW-reinitiation on initial pressure: l – channel width, R – curvature's radius of boundary

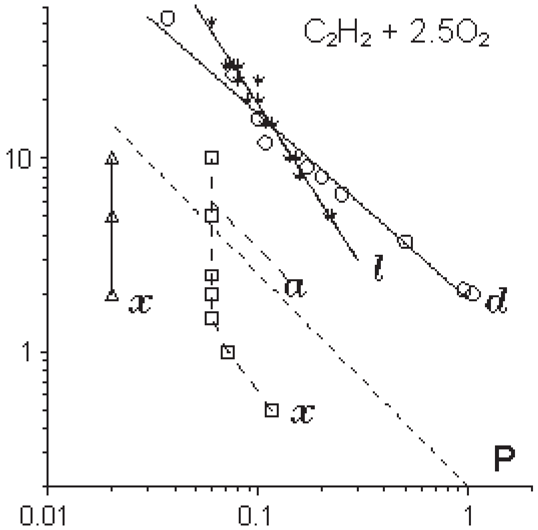

Fig. 17. Summary graph of critical conditions of DW-reinitiation on initial pressure for spherical (d-line), cylindrical (l-line) and plane (x-lines) symmetries

luted by Ar or He (to 90%) have demonstrated that the critical values of parameters l_{**}/a and d_{**}/a change as the inert gas concentration rises, their variation is most appreciable at high concentrations. Nitrogen influences the process in a similar way. The results of experiments are demonstrated on Fig. 18, critical diffraction diameter – in mm. Symbols on all graphs correspond to experimental data, the lines – calculated data with the help of Code SAFETY for estimation of detonation hazards of different combustible mixtures [34-35].

Conclusions

Extensive experimental investigations of DW-diffraction were carried out for different fuel-oxygen and fuel-air mixtures in wide variation of the main parameters – pressure, temperature, stoichiometric ratio, dilution degree by inert gases… The great bank of experimental data is created.

The traditional criteria of DW-reinitiation d_{**}/a = const was analyzed carefully. It was established that such criteria can used for rough estimation only. Value d_{**}/a varies at least within a factor of 2 for different mixtures from traditional value, and especially for high-diluted mixtures and over-driven DW.

It was established that the efficiency of reinitiation processes can be increased and optimized by many ways: change of symmetry type, use of ring initiator, multi-pointed initiation, reflection from wall, … At optimal space and spatial ratio the critical initiation energy can be reduced up to order.

Experimental data are well predicted by calculations.

The presented experimental and calculated data can be used at optimization of PDD for utilization of worn-out tires.

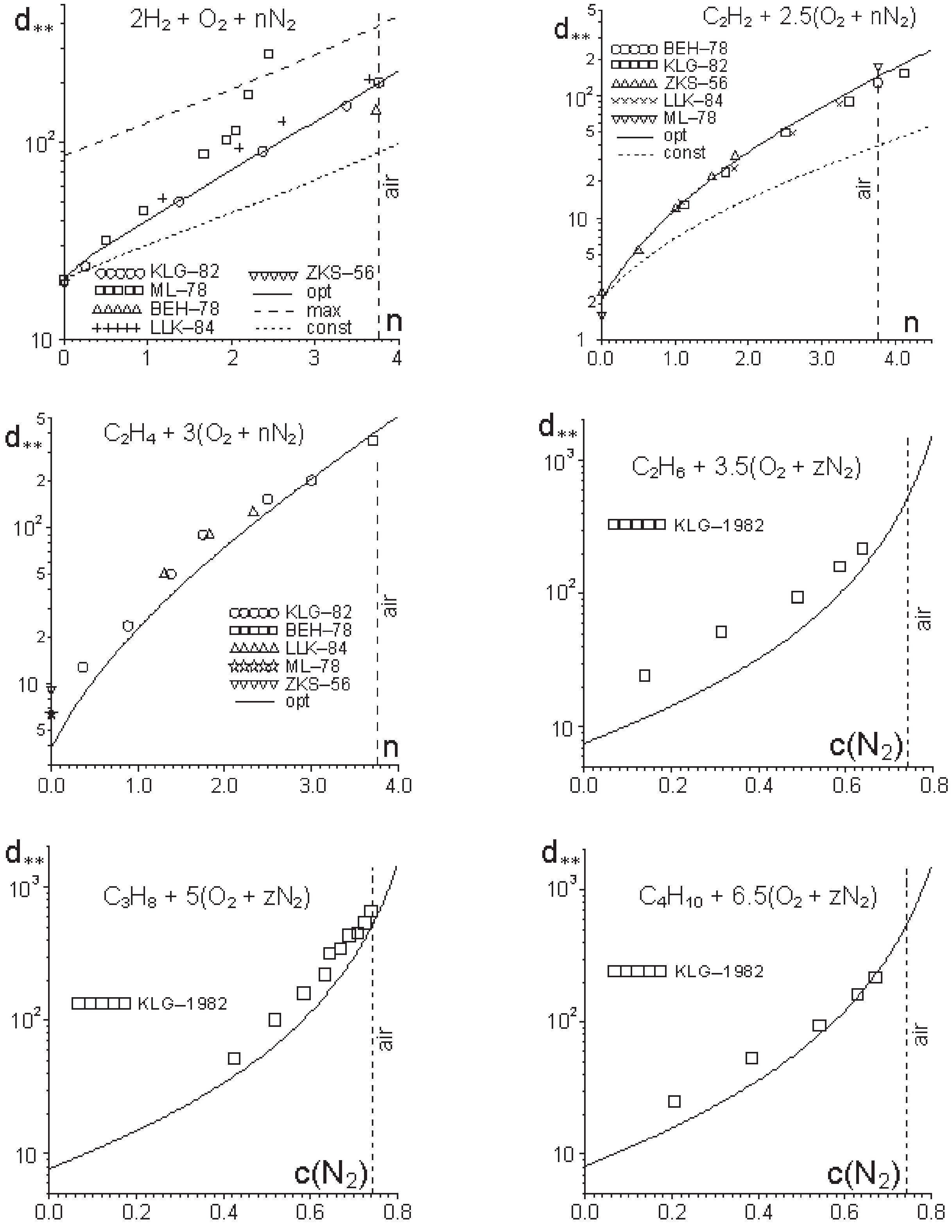

Fig. 18. Critical diffraction diameter (mm) on molar numbers of nitrogen.

Acknowledgement

The work was supported by the INTAS Project 01-0792.

References

1. Baklanov D., Desbordes D., *et al.* Proceeding of 19-ICDERS, Hakone, Japan, 2003. CD ISBN

4-9901744-1-0 C3053. No 008
2. Campbell C., J. Chem. Soc. 2483 (1922).
3. Laffitte P., Com.-Rend. Acad. Sci. 177, 178 (1923).
4. Zeldovich Ya.B., Kogarko S.M., Simonov N.N., Zh. Tekhn. Fiz. 26, No 8, 1744 (1956).
5. Voitsekhovskii B.V., Mitrofanov V.V., Topchian M.E., Struktura Fronta Detonatsii v Gazakh (Structure of the Detonation Front in Gases) (Izd. SO AN SSSR, Novosibirsk, 1963).
6. Mitrofanov V.V. and Soloukhin R.I., Dokl. Akad. Nauk SSSR 159, No.5, 1003 (1964).
7. Vasil'ev A.A., Candidate-of-Science Thesis (Phys. Math.) (Novosibirsk, 1977).
8. Vasiljev A.A. and Nikolaev Yu.A., Acta Astron. 5, 983 (1978).
9. Vasil'ev A.A., Fiz.Goreniya Vzryva 14, No 3, 154 (1978).
10. Vasil'ev A.A., Nikolaev Yu.A., and Ul'yanitskii V.Yu., Fiz.Goreniya Vzryva 15, No 6, 94 (1979).
11. Vasil'ev A.A. and Grigor'ev V.V., Fiz.Goreniya Vzryva 16, No 5, 117 (1980).
12. Knystautas R., Lee J.H., and Guirao C.M., Combust. Flame 48:63 (1982).
13. Westbrook C.K. and Urtiew P.A., 19th Symp. (Intern.) on Combustion, The Combustion Inst., Pittsburgh, 1982, p. 615.
14. Lee J.H., Ann. Rev. Fluid Mech. 16, 311 (1984).
15. Benedick W.B., Guirao C.M., Knystautas R., *et al.*, Progress in Astronaut. and Aeronaut., Vol. 106, New York, 1986, p. 181.
16. Vasil'ev A.A., Doctor-of-Science Thesis (phys. Math.), Novosibirsk, 1995.
17. Kogarko S.M., Izv. Akad. Nauk SSSR, Ser. Khim. No 4, 419 (1956).
18. Hiramatsu K., Fujiwara T., Taki S. 20-th Symp. (International) on Combust. The Combustion Institute, Pitsburg, 1984.
19. Fisher M., Pantow E., Kratzel T. in G.Roy, S.Frolov, K.Kailasanath, N.Smirnov Eds., Gaseous and Heterogeneous Detonations. Science to Applications. ENAS Publishers, M., 1999, pp. 197-212.
20. Khasainov B., Priault C., Presles H.-N., Desbordes D. 18-ICDERS Procceeding, Seattle, USA. University Washington, 2001. CD ISBN 0-9711740-0-8. No 096.
21. Strehlow R.A. and Salm R.J., Acta Astron. 3, No 11, 983 (1976).
22. Desbordes D. and Vachon M., Progress in Astronaut. and Aeronaut, Vol. 106, New York, 1986, p. 131.
23. Benedick W.B., Knystautas R., and Lee J.H., Progress in Astronaut. and Aeronaut., Vol. 94, New York, 1983, p. 546.
24. Liu Y.K., Lee J.H., and Knystautas R., Combust. Flame 56:215 (1984).
25. Vasil'ev A.A., Dinamika Sploshnoi Sredy (Dynamics of Fluids), Novosibirsk, 1987, No 80, p. 41.
26. Moen J.O., Sulmistras A., Thomas, et al., Progress in Astronaut. and Aeronaut., Vol. 106, New York, 1986, p.220.
27. Vasil'ev A.A., Fundamewntal'nye Problemy Fiziki Udarnykh Voln (Fundamental Problems of Shock Waves), Divis. of Inst. of Chemical Phys., Chernogolovka, 1987, p.142.
28. Vasil'ev A.A., Fiz. Goreniya Vzryva 24, No 2, 118 (1988).
29. Vasil'ev A.A, Fiz. Goreniya Vzryva 25, No l, 113 (1989).
30. Vasil'ev A.A, Fiz. Goreniya Vzryva 20, No 6, 142 (1984).
31. Strehlow R.A., Adamczyk A.A, and Stiles R.J., Astron. Acta 17, No 4-5, 509 (1972).
32. Edwards D.H., Thomas G.O., and Nettleton M.A., J. Fluid Mech. 95, No l, 79 (1979).
33. Bannikov N.V.and Vasil'ev A.A , Fiz. Goreniya Vzryva 29, No 3, 164 (1993).
34. Vasil'ev A.A. Combustion and Detonation. Proc. 28-th Inter. ICT-Conference. Fraunhofer Ins. Chem. Technology, Karlsruhe, Germany 1997. pp. 1-50.
35. Vasil'ev A.A., Valishev A.I.,Vasil'ev V.A., Panfilova L.V. Combustion, Explosion&Shock Wave 36, No 3. pp. 81-96 (2000).

Received 29 September 2003.