DISCRETE STRUCTURE CHANGE IN A GAS-DETONATION WAVE

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It has been shown [1, 2] that the pitch Δx of a pulsating detonation along the tube wall has a discrete dependence on the initial pressure p_0, as do other parameters such as the frequency ω.

We have examined detonation in $2H_2 + O_2$ in a brass tube 4 m long with inside diameter d = 16 mm. In the first 1.5 m was a wire spiral, which accelerates [3] the conversion of burning to detonation. The rest of the smooth tube was of constant cross section. The other end of the tube was attached by means of a vacuum joint to a 1-m glass tube having an inside diameter of 16 ± 0.2 mm. The recordings were made photographically with a ZhFR-1 apparatus [4] and by the trace method [1].

Special attention was given to providing constancy of the other conditions when p_0 was varied. The mixture was fired by fusing a wire, which ignited the mixture, which then went on to detonate.

We varied p_0 from 100 to 300 mm Hg by steps of 10 mm Hg and from 300 to 900 mm Hg by steps of 100 or 200 mm Hg; 10-20 runs were made at each p_0, and the runs at the various p_0 were numbered n = 1, 2, 3, ... (the order) [1, 5, 6]. The first order had spin and pulsating detonations with n = 1, so the spin detonation was denoted by n' = 1. The means $\langle n \rangle$ and $\langle \Delta x \rangle$ and detonation rate $\langle D \rangle$ were used to find

$$\langle \omega \rangle = \langle D \rangle / \langle \Delta x \rangle, \qquad \langle \mathrm{tg}\alpha \rangle = \pi d / \langle n \rangle \langle \Delta x \rangle, \tag{1}$$

in which α is the inclination of the fracture trace to the generatrix of the tube.

Table 1 gives the parameters for 130-300 mm Hg, which reveal clearly the discrete change in the detonation structure. At p_0 = 100 mm Hg, ten tests gave no instance of detonation (only burning was observed). At 110 and 120 mm Hg, 20 tests gave four cases of spin detonation with n' = 1, but burning in the others. The minimum pressure p_0^* for a self-maintaining pulsating detonation with n = 1 was 130 mm Hg, and this was used to normalize the axis of p_0, while on the pulsation axis we plotted $\pi d / \langle \Delta x \rangle$, since $\langle \Delta x \rangle \approx \pi d$ for n = 1.

The data were processed by smoothing [7] to give the formula

$$\frac{\pi d}{\langle \Delta x \rangle} = \left[\left(\frac{\langle p_0 \rangle}{p_0^*} - c \right) a \right]^r. \tag{2}$$

Figure 1 shows the results, in which points 1 are our results, points 2 are from [8, 9], and points 3 are from [10]. The observed points correspond approximately to definite n for the mean $\langle p_0 \rangle$ and $\langle \Delta x \rangle$,

Table 1

n	p_0, mm Hg	D, m/sec	Δx, mm	ω, kHz
1	137±5	2333±74	50±1.7	46±2
2	136±6	2320±174	32±2	72±6
3	137±6	2375±89	21±2	112±5
4	150±9	2438±50	16±1	154±9
5	165±7	2484±50	13.6±0.8	186±10
6	174±8	2507±86	11.8±0.4	213±9
7	194±6	2540±52	10.1±0.3	252±10
8	203±8	2563±90	9.1±0.5	282±16
9	220±6	2572±60	8.1±0.3	320±13
10	227±10	2649±51	7.4±0.2	353±15
11	242±9	2680±36	6.8±0.2	390±16
12	254±10	2674±33	6.2±0.2	417±15
13	271±7	2678±52	5.6±0.1	461±12
14	288±8	2730±40	5.2±0.1	512±14
15	300	2736±46	4.75±0.05	556±12

though with some overlap along the axis of $\xi = \lg(\langle p_0 \rangle / p_0^* - c)$, since different n occurred with equal probability for a given p_0 in certain tests. On the other hand, there was clear bunching of the results up to fairly high n along the axis of $\eta = \lg(\pi d / \langle \Delta x \rangle)$. Least-

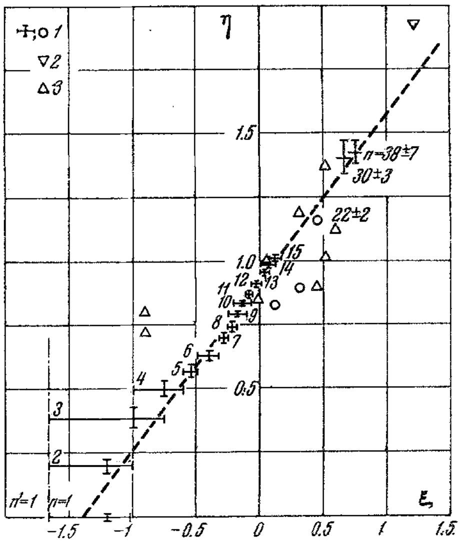

Fig. 1. Dependence of Δx on p_0 for $2H_2 + O_2$ in a tube with an inside diameter of 16 mm.

squares fitting gave the constants of (2) as r = 0.663, a = 25.7, and c = 0.978, and so we have the following for (2):

$$\frac{\pi d}{\Delta x} = \left[\left(\frac{p_0}{130} - 0.978 \right) \cdot 25.7 \right]^{0.663}, \tag{3}$$

in which d and Δx are in mm, while p_0 is in mm Hg.

Formula (3) resembles earlier formulas [6, 10] in not showing the discrete variation of Δx with n; but the data of Table 1 may be worked up in terms of the differences of the Δx for adjacent n to give

$$\frac{\pi d}{\Delta x} = \frac{1}{n} + \zeta \left(1 + \frac{1}{n} \right)(n - 1), \tag{4}$$

in which ζ is a constant to be determined from normal equations of a type similar to (4) via the data of Table 1, which give $\zeta = 0.7$. For large n, (4) becomes

$$\pi d / \Delta x = \zeta n. \tag{5}$$

Formula (3) is convenient for calculating Δx and may be used to extrapolate to large p_0, where Δx and n cannot be determined by experiment. For instance, Table 2 gives parameters calculated from (1), (3), (5), and (6) for the detonation waves produced by Troshin and Shchelkin [8, 9] and by Schmidt [11] in $2H_2 + O_2$ at p_0 of 3, 420, 500, 760, and 800 atm. The Δx given by (3) for these p_0 were used in (5) to find the corresponding n, and then via the formula [9]

$$\tau = \frac{\Delta x (\gamma + 1)(1 - \sqrt{(\gamma - 1)/2\gamma})\, \mathrm{tg}\,\alpha}{2D(\gamma - 1)} \tag{6}$$

and the measured D [11], we can readily deduce the ignition induction time τ at temperatures T_1 given by

$$T_1 = T_0 \left[\frac{4\gamma - (\gamma - 1)^2}{(\gamma + 1)^2} - \frac{2(\gamma - 1)}{(\gamma + 1)^2 M_1^2} + \frac{2\gamma(\gamma - 1)}{(\gamma + 1)^2} M_1^2 \right],$$

$$\left(M_1 = \frac{D}{c_0} \right), \tag{7}$$

Table 2

	p_0, atm	D, m/sec	Δx, mm	$M_1 = \frac{D}{c_0}$	(3) Δx, mm	(5) n	(1) ω, MHz	(6) τ, μsec	(7) T_1, °K
[8,9]	3	2850	0.6	5.55	0.9	120	4.75	0.275	2010
[11]	420	3500	—	6.8	0.034	2120	100	0.013	2880
	500	3600	—	7.0	0.030	2400	120	0.011	3030
	760	4250	—	8.27	0.023	3130	185	0.007	4115
	800	4440	—	8.65	0.022	3270	200	0.0065	4280

in which M_1 is the Mach number, T_0 is the initial temperature, and γ is the polytropy constant. This gives τ as less than 10^{-8} sec, which

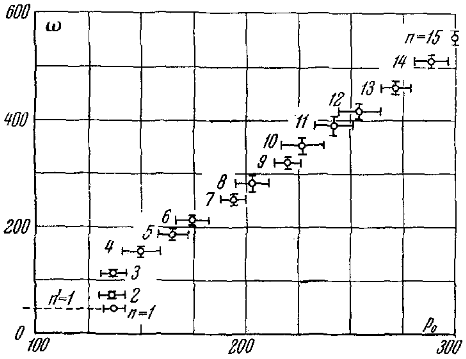

Fig. 2. Spectrum $\omega(p_0)$ of detonation frequencies.

approaches the limiting time for chemical reactions, which is governed by the excitation time for the vibrational degrees of freedom in molecules.

Comparison of the second formula in (1) with (5) shows that ζ has the simple physical meaning of $(\tan \alpha)_{min}$; in fact, the $\tan \alpha$ calculated from (1) by means of measured $\langle \Delta x \rangle$ and $\langle n \rangle$ becomes $(\tan \alpha)_{min} \approx 0.7$ for $n \geq 6$.

The dependence of ω on p_0 also is markedly discrete; Fig. 2 shows the results for n of 1–15, with ω in kHz and p_0 in mm Hg. It is clear that $\omega(\langle p_0 \rangle)$ is a linear relation, with deviations only for n of 1 and 2, where there is a tendency to produce spin detonations with $n' = 1$ and where we are close to the limit for the propagation of detonation waves.

The results show that there is discrete variation in the structure of a detonation wave as the initial conditions vary, which is further proof of the pulsation mechanism for propagation of detonation waves in gases. The empirical relations allow one to obtain extrapolation estimates for the effective induction period for ignition at high temperatures.

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