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SHORTER COMMUNICATIONS

THE MECHANISM OF SPINNING DETONATION*

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NOMENCLATURE

p_1, initial pressure;
p_3, final pressure;
$p_{3'}$, detonation pressure;
p_{3+}, pressure file;
D_v, shock speed;
D_0, axial speed of spinning detonation;
D_D, speed of detonation head;
D'_D, detonation speed;
P, pitch;
d, tube diameter.

INTRODUCTION

THE THEORETICAL work on spinning detonation [1] is devoted to the detailed evaluation of experimentally obtained wave diagrams. With the known relations for shocks, detonations and triple points the flow field, the pressures and temperatures produced by the waves, are calculated and controlled by experimental data. Besides, an acoustical treatment [2] yields a relation for the pitch. It leaves aside propagation velocity of the detonation head and the actual pressures which by far are not infinitesimal. Hence an occasional agreement with experiments cannot be valued as confirmation of this relation. One therefore still asks why the spinning detonation acts as it does. As will be shown its mechanism can be derived from fundamental facts without leaning on experimental evidences. A close agreement with experiments is achieved with respect to pitch, propagation velocity, pressures and wave diagrams.

MECHANISM OF SPINNING DETONATION

For the first it is useful to use a simplified scheme of the beginning of a spinning detonation. Suppose that by artificial ignition at the closed end of a duct a burned layer is generated from which there emerges an axially propagating shock. Since near-limit mixtures are in question the shock will not ignite the gas continuously. However, in the unburnt layer behind the shock accidentally a fast local combustion will occur preferably at the wall where pressures are enhanced by reflection of the instantaneously created shocks. Since the gas is more reactive behind than in front of the shock this combustion will spin as detonation head close behind the shock front along the wall. This occurs preferably in one direction because of asymmetries with which detonations usually start [3].

This view puts attention to the displacement of the burnt gases which supports the axially propagating shock on the unburnt gas column. It is evident, that in the first step of approximation the final pressure p_3 (Fig. 1) behind the spinning detonation is equal to that of a normal axially propagating detonation $p_{3'}$ (Fig. 2). Since this pressure results from the expanding burnt gases it determines the axially propagating shock which paves the way for the spinning detonation. Hence the speed of this shock D_v (Fig. 1) is the axial component of the speed of the detonation head. The detonation head can be treated as a normal detonation since it compares well with the front part of a detached shock at a blunt body. The displacement of the body here is replaced by that of the reacting gases. Thus the Chapman–Jouguet theory can be used to determine the circumferential speed of the front part of this head which is indicated schematically by a short dashed line in Fig. 1.

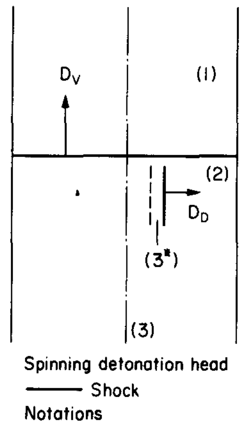

FIG. 1. Spinning detonation head. ——, shock.

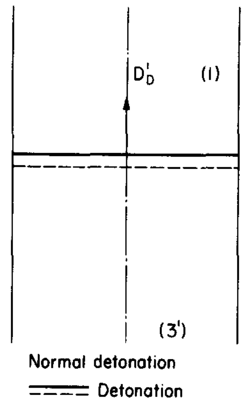

FIG. 2. Normal detonation. ═══, detonation.

Extensive numerical computations on detonations are at hand considering chemical equilibrium of the constituents [4]. They refer to the mixtures used in experiments, i.e. mixtures of H_2–O_2, CO–O_2, CO–O_2–H_2O, CO–O_2–H_2 and C_2H_2–O_2 without and with admixed argon or helium in concentrations as they were used in experiments [5–7]. The considered particles in the first case are H_2, O_2, H, O, H_2O, OH, in the second CO, CO_2, O_2, O, in the third and fourth additionally H_2, H, H_2O, OH, and in the last case O_2, O, H_2, H_2O, OH, CO, CO_2, C, CH, CH_2, CH_3, CH_4, C_2H_2, HCO.

* See also: Report 4/73 Ernst-Mach-Institute, Freiburg, W. Germany, Eckerstasse 4.

Table 1. Wave velocities, pressure and temperature ratios, pitch to diameter ratio

Mixture		p_1 (torr)	T_1 (K)	$\frac{p_3}{p_1}$		D_v (m/s)	D_D (m/s)	$\frac{P}{d}$	$\left(\frac{P}{d}\right)_{exp}$	$\left(\frac{P}{d}\right)_F$	D'_D	D_0	$\left(\frac{p_3}{p_1}\right)_{exp}$	$\frac{p_{3*}}{p_1}$	$\left(\frac{p_{3*}}{p_1}\right)_{exp}$
$2CO+O_2+3\%H_2$	[6]	76	298	17.2	1.4	1332	1723	2.42					20	126	160
$6.7\%C_2H_2+10\%O_2+83.3\%A$	[7]	44	298	19.26	1.61	1280	1633	2.47	2.68	2.35	1639	1300			
$40\%C_2H_2+60\%O_2$	[7]	30	298	35.31	1.32	1844	2642	2.2	2.68	2.97	2514	2000			
$5\%C_2H_2+7.5\%O_2+87.5\%A$	[7]	18	298	16.73	1.62	1192	1529	2.43	2.68	2.35	1573	1330			
$2H_2+O_2+85\%A$	[5]	190	298	12.52	1.63	1085	1463	2.34	2.55	2.71	1428				
	[5]	760	298	18.82	1.4	2175	2825	2.42	2.6	3.14	2840				

RESULTS

Table 1 compares theory with experiment. The speed of the axially propagating shock D_v compares with the measured axial component of the propagating speed of the spinning detonation which is denoted by D_0. With C_2H_2 as reactant, D_0 was measured and showed to be $80 \div 90\%$ of the speed D'_D of an axially propagating detonation [7]. Calculating D'_D and multiplying by the average experimental value 0.85 one obtains values of D_0 which agree quite remarkably with D_v.

The pitch P to diameter d ratio is determined by

$$\frac{P}{d} = \pi \frac{D_v}{D_D}$$

D_D is the circumferential speed of the detonation head which penetrates behind the shock front in a gas with the state (2) which has the same pressure as state (3). The ratio P/d compares well with the experimental ratios $(P/d)_{exp}$. A minor systematic deviation exists whilst the acoustic theory presented by $(P/d)_F$ deviates randomly. The systematic deviation shows that the displacement of the burnt gases is inserted somewhat too low in this first step of approximation.

The calculated pressures correspond to the extremely high pressures which were measured [1, 6]. They result from the detonation of a gas which is precompressed by the axially propagating shock. This two step compression is in agreement with the experimental work [1, 7]. Especially interesting is the agreement of the calculated v. Neumann pike p_{3*} with the experimental pressure pike $p_{3*_{exp}}$. The difference between the theoretical value, 126 and the experimental value, 160, is due to the well-known fact that pressure transducers with small diameters react with a considerable overshoot to sudden pressure increases.

Indeed the pressure profiles depict a strong natural frequency which does not allow to determine the final pressure p_3 exactly. However, the average $p_3 = 20$ atm compares quite well with the calculated pressure $p_3 = 17.2$ atm. Their exists furthermore in principal coincidence with the experimental wave diagrams [1, 7] which depict the axially propagating shock denoted as primary shock front [7], as well as a detonation head propagating helically in an unburnt layer behind the primary shock.

The experimental wave diagrams furthermore show a deformed primary shock front. It comes from the interaction with the shock emerging from the detonation head. This interaction is not considered in the first step of approximation. Besides, the part of this shock penetrating the burnt gas influences its pressure. It underlies a complicated overlapping on account of the helical propagation which enables the correction of the displacement. However, when considering the limits of accurateness of measurements the first step of approximation yields sufficient agreement with respect to the main properties.

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