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On the Detonation Wave Propagation

J.-M. Chevalier⁽¹⁾

Commissariat à l'Energie Atomique, CEV-M, BP. 7, 77181 Courtry, France

A new theoretical approach of the unsteady detonation in condensed explosives was developed. The first experimental results presented in this paper confirm that the evolution of the front can be described by the propagation of front-waves, as predicted by the model. It seems, also, that the speed of these waves is a decreasing function of detonation velocity and doesn't depend on the confinement of the explosive.

INTRODUCTION

A new model describing the detonation front propagation in condensed explosives (named Jr model) has been recently proposed by L. Brun [1-2]. First macroscopic model of the unsteady detonation, the Chapman-Jouguet model [3] assumes an instantaneous and complete decomposition across a downstream sonic discontinuity. But the condition of a detonation propagation at constant velocity doesn't agree with the curved steady revolution detonation (SRD) fronts observed on condensed explosives. The Zeldovitch-Von Neuman-Döring model ZND [4-5] assumes that the decomposition goes on behind a non reactive and hence subsonic discontinuity. The ZND model agrees for interpretations of the SRD [6], but appears difficult to extend to unstationnary cases like spherically diverging detonation.

In Jr model, the front acceleration is related to its curvature by two functions of the local detonation velocity: the characteristic curvature, which has been already studied (Aveillé, Bdzil) [7-11], and a new function, the characteristic speed, which describes the propagation of front-waves.

Original experiments was performed in order to check the model, in TATB and HMX based compositions, to confirm the front-waves propagation.

THE Jr MODEL

Three assumptions govern the model. The detonation front is assimilated to an infinitely thin and downstream sonic discontinuity. But this model does not suppose, as Jouguet's did, a total decomposition within the front, and thus accordingly releases Jouguet's condition $D=D_{cj}$ [1]. The acceleration of a self-sustained detonation wave front is given by the relation:

$$\delta D / \delta t = 2 C^2(D) [K(D) - \mathcal{C}],$$

where $\mathcal{C}$ is the curvature of the front, $C(D)$ the velocity of the front-waves and $K(D)$ the celerity-curvature relationship.

(1) At present, Commissariat à l'Energie Atomique, CESTA, BP. 2, 33114 Le Barp, France

The associated boundary condition is:

$$B(\theta_b, D_b) = 0,$$

where θ_b is the front inclination on the unperturbed interface and D_b the front velocity at the boundary.

The characteristic angle connects the front-wave speed with the detonation velocity by the relation:

$$\tan \varphi = C(D)/D$$

ASSOCIATED EXPERIMENTS

The Jr model can easily be used to describe what would happen in a cylindrical geometry: if a steady detonation propagates in an explosive cylinder, a sudden reduction of the diameter generates a circular perturbation which propagates inwards.

As shown figure 1, the model tells that, if the perturbation starts at time t_0 , at $t_0 + dt$ a length Cdt of the front will be modified. The TT' surface is not yet affected, and is determined by a translation of the NN' surface.

These phenomena must be experimentally observed in order to check the model.

FIGURE 1 : DISPLAY PRINCIPLE OF FRONT WAVES

EXPERIMENTAL SET-UP

The experimental set-up used to observe the detonation front and to measure the front-wave speed is presented figure 2.

A plane wave generator initiates a detonation wave in an unconfined explosive cylinder (diameter ϕ_1). Its length H_1 is chosen in order to achieve a steady detonation. The cylinder free surface is metallized for the optical recording of the front motion.

An argon flash-light is reflected by the surface and focused on a streak camera. When the

detonation wave interacts with the surface, the damage of the metal spray is recorded on the film.

In another experiment a cylinder of diameter ϕ_2 ($\phi_2 < \phi_1$) and length H_2 is added to the previous one, and the detonation front is observed by using the same technics. Comparison of the shapes of the waves which emerge from both cylinders yields the velocity of the front-waves.

FIGURE 2 - DISPLAY EXPERIMENTAL SET-UP OF FRONT WAVES IN EXPLOSIF.

EXPERIMENTAL RESULTS

TATB BASED COMPOSITION T2 (97 % TATB)

In order to study the variation of the front-waves speed C versus the detonation velocity D , several cylinder diameters ϕ_1 have been tested. For T_2 composition, as for others TATB compositions, the detonation velocity is strongly dependent on the cylinder diameter (Aveillé) [10-11].

Figure 3 presents the optical records obtained in one configuration. In the first experiment, the dimensions were $\phi_1=30$ mm, $H_1=120$ mm. In the second experiment, a cylinder $\phi_2=15$ mm, $H_2=15$ mm is added.

No noise perturbs the records. The superposition of the two measurements gives an accurate determination of the front-waves speed. The central part of the front, delimited by the two points T and T', is not yet affected by the perturbations propagated by the front -waves, as predicted by the Jr model.

As defined figure 1, D and C are given by the relation : $D=NT/dt$, $C=PN/dt$. C is the average value of the front waves velocity. D is in good agreement with previous measurements [10-11].

The values of C(D), reported in table 1, show that C is a decreasing function of D [12].

FIGURE 3 - EXTENDING SUPERPOSITION OF $T_2 \phi_1=30$ AND $\phi_2=15$ WAVES OUT

TABLE 1 - MEASURED VALUES ON T_2 COMPOSITION

Φ_1/Φ_2 (mm)	H_2 (mm)	D (m/s)	C(D) (m/s)	ϕ (°)	ΔD (m/s)	ΔC (m/s)	$\Delta \phi$ (°)
30/15	15	7538	2810	20.4	35	250	2
		7519	2810	20.5	35	250	2
75/50	40	7627	1880	13.8	20	140	1
100/50	40	7603	2170	15.9	20	140	1

To complete the determination of function C(D), a serie of experiments have been realised with cylinder diameters f_1 decreasing from 75 to 10 mm. In these conditions the detonation velocity decreases from 7630 to 7290 m/s [10-11]. The measured values of C(D) are reported on table 2. The variations of front-waves speed C versus the detonation velocity are recorded on figure 4. These results confirm that C is decreasing function of D. The last value seems to

express that the front-wave speed increases strongly near the critical diameter ($\phi_c=8.5$ mm for T_2 composition). Nevertheless, this value needs to be confirm.

TABLE 2 - STUDY OF THE C(D) FUNCTION ON T_2 COMPOSITION

Φ_1/Φ_2 (mm)	H_1 (mm)	H_2 (mm)	D (m/s)	C(D) (m/s)	ϕ (°)	ΔD (m/s)	ΔC (m/s)	$\Delta\phi$ (°)
75/50	510	40	7626	1990	14.6	8	100	0.8
60/40	370	30	7612	1990	14.7	10	130	1
40/20	240	14	7560	2320	17.1	20	140	1
30/15	160	10	7558	2490	18.2	30	200	1.5
20/14	100	9	7502	2670	19.6	30	220	2
15/10	75	4	7438	3350	24.2	70	400	3
		6	7413	3210	23.4	45	270	2
10/6	50	2	7326	5860	38.7	135	840	6

In a second study two experiments series have been performed to observe the variation of front-wave speed C with the time.

In this case, configurations with $\phi_1=50$ mm, $\phi_2=30$ mm and $H_2=10$ to 50 mm by 10 mm step has been tested. For this configuration the detonation velocity on the axis wouldn't vary.

The experimental results are reported on table 3. The measured values of C confirm that to one detonation velocity value D is associated one front-wave speed C, taking the experimental accuracy into consideration.

HMX BASED COMPOSITIONS X1 AND X2 (96 ET 94,2% HMX)

These two HMX based compositions differ essentially by their binders. The measured values of C(D) [12] are reported in table 4.

In both compositions, the values are nearly the same, as expected, and lower than those found for the TATB composition.

For the experiments on HMX compositions, decrease of the detonation velocity is not significant enough to check whether function C(D) is decreasing or not.

TABLE 3: MEASURED VALUES OF FRONT-WAVES SPEED VERSUS THE TIME ON T₂ COMPOSITION

Φ_1/Φ_2 (mm)	H ₁ (mm)	H ₂ (mm)	D (m/s)	C(D) (m/s)	ϕ (°)	ΔD (m/s)	ΔC (m/s)	$\Delta\phi$ (°)
50/30	300	10	7612	2090	15.4	30	390	3
		20	7607	2020	14.9	15	195	1.5
		30	7607	1990	14.7	10	130	1
		40	7606	2170	15.9	8	65	0.5
		50	7609	2025	14.9	6	40	0.5

Figure 4 - Variation of front-waves speed C versus the detonation velocity

TABLE 4 - MEASURED VALUE ON X₁ AND X₂ COMPOSITION

Composition	Φ_1/Φ_2 (mm)	H ₂ (mm)	D (m/s)	C(D) (m/s)	ϕ (°)	ΔD (m/s)	ΔC (m/s)	$\Delta\phi$ (°)
X ₁	25/10	20	8755	1450	9.4	40	100	1
X ₁	50/30	30	8744	1530	9.9	25	100	1
X ₂	100/50	40	8767	1420	9.2	20	100	1
X ₂	100/50	80	8760	1320	8.5	10	100	1

INFLUENCE OF THE CONFINEMENT

The Jr model predicts that C is a function of the detonation velocity and will not depend on the boundary conditions. Some experiments were performed with an aluminum case around the second explosive cylinder. The results are given in table 5.

TABLE 5 - INFLUENCE OF THE CONFINEMENT COMPOSITION

Confinement	Φ_1/Φ_2 (mm)	H ₂ (mm)	D (m/s)	C(D) (m/s)	ϕ (°)	ΔD (m/s)	ΔC (m/s)	$\Delta\phi$ (°)
Air	100/50	40	8767	1420	9.2	20	100	1
2024			8787	1370	8.9	20	100	1
Air	100/50	40	7603	2170	15.9	20	140	1
Steel			7646	2060	15.1	20	140	1
2024			7651	1940	14.2	20	140	1

The measured values of C , with and without confinement, are very close to each other. Of course, the shapes of the detonation fronts are very different : the front-waves move with the same speed, but they do not carry the same information.

UNSTEADY REGIME

In the experiment depicted on figure 5 the detonation was initiated in a cylinder of T_2 composition by a plane detonation making an angle of 74° with the axis. It appears that the detonation in the T_2 cylinder evolves towards the stationnary shape which would be observed when initiation is perpendicular to the axis.

Indeed several configurations have been performed with T_2 cylinders which dimensions are respectively $\phi=50$ mm and $H=100, 200, 400$ and 600 mm. For the first, the optical record presented (figure 6) shows an assymetrical detonation front with regard to the axis. For the third, the detonation front (figure 7) was setted partly, presenting a weak assymetry.

For this configuration, the perturbation due to the diameter reduction and which propagates inwards, is arrived at cylinder center and is came back two times before the detonation emergence. For the last, the recorded detonation front was setted and presents the same characteristics as a detonation front with a perpendicular to the axis initiation.

Figure 5 - Experiences in unsteady detonation field **FIGURE 6 - Optical record of detonation in T₂ cylinder ($\Phi=50$ mm et H=100 mm) initiated by a plane detonation making an angle of 74° with the axis** **FIGURE 7 - Optical record of detonation in T₂ cylinder ($\Phi=50$ mm et H=400 mm) initiated by a plane detonation making an angle of 74° with the axis**

FIGURE 8 - Experimental set-up of the zero method for boundary condition determination

ASSOCIATED BOUNDARY CONDITION

For this study, two methods were used to measure the front inclination. The first (classical method) is based on the front detonation record at the end of explosive cylinder. For the second (zero method), this cylinder is terminated in cone ("pencil") with an inclination q_b corresponding to the presumed value. This method allows a more accurate measure of the motion at this presumed value. The experimental set-up of this method and the optical record obtained for T_2 cylinder with 30 mm diameter are presented respectively figures 8 and 9. Measures were obtained after digitalization and linear approximation on 0.7 mm of boundary front wave. The measured values for T_2 composition are showed on table 6. The boundary detonation velocity is given by the relation $D_b = D \cdot \cos q_b$, where the D values were measured by Aveillé and Col. [10-11]. The classical method, though less accurate, is given interesting results.

FIGURE 9 - Optical record for T_2 "pencil" ($\phi=30$ mm et $H=180$ mm)

TABLE 6 - MEASURED VALUES OF THE BOUNDARY CONDITION ON T₂ COMPOSITION.

(Zéro method))			(Classical method)	
Φ (mm)	D_b (m/s)	Θ_b (°)	D_b (m/s)	Θ_b (°)
50			7145	20.1
40			7095	20.2
30	7095	19.8	7110	19.8
20	7020	20.7	7065	19.6
15	6885	22.7	6925	21.1
10			6450	28.3
9			6340	29.6

$$\Delta\Theta_b \sim 1^\circ$$

CONCLUSION

The experimental results presented in this paper are in general agreement with the front wave propagation phenomena as described by the Jr model. They were obtained for TATB or HMX based compositions, which exhibit very different front curvatures and these preliminary results seem to confirm the basic assumption of a front-wave speed that only depends upon the detonation velocity.

The results on TATB based composition show that C is a decreasing function of D. Experiments performed on HMX based compositions can't lead to same conclusions. Results on TATB (C(D) function associated with the boundary condition values) would certainly allow to treat more physically the detonation in calculations.

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