

Similarity Deviation of Diameter and Thickness Effects

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ABSTRACT

One way to characterize the similarity of detonations (in the sense of their reaction rate) is through size effect tests. Using cylinders (rods), they're called diameter effect tests, and using slabs, they're called thickness effect tests. From the steady state equations of motion of these configurations it follows that they scale as $r(D)=h(D)$, where r =rod radius, h =slab thickness, and D =steady detonation velocity. But tests show deviations from such scaling. Here we propose an explanation to these deviations. The explanation is based on a previous work in which we show that a boundary layer of partial reaction usually forms when a detonation wave is grazing along a free boundary. We suggest and show via computer simulations that those scaling deviations are related to this partially reacted boundary layer effect.

INTRODUCTION

It is customary to characterize sensitivity or insensitivity (in the sense of reaction rate in a detonation wave) of explosives in terms of a size effect test. When the test explosive is a long cylinder, it is known as the diameter effect test. In this test we shock initiate the explosive cylinder (which is unconfined) at one end, and measure the steady detonation velocity after the detonation wave has travelled a distance of several diameters. As is well known, the steady detonation velocity (D) is lower for cylinders with a smaller diameter (d), and there exists a failure diameter (d_f) under which the detonation wave decays and steady detonation is not reached. Usually, we perform detonation velocity tests with cylinders of different diameters, and plot the results as a $D(1/d)$ curve called the diameter effect curve. We can then extrapolate to $1/d=0$ which represents a large diameter cylinder, and find the detonation velocity D_0 which is a reasonable approximation to the plane wave detonation velocity of the explosive (D_{CJ}).

When the diameter effect curve of an explosive is flat (detonation velocity doesn't change much when the diameter increases), the explosive is regarded as ideal. This would happen for explosives with high reaction rate and a narrow reaction zone. A good example of an ideal explosive is a pressed HMX based mixture like PBX9501, with a reaction zone thickness of a few tenths of a mm. An explosive with a more steeply descending diameter effect curve is regarded as semi-ideal, and a common example for that are TATB based explosives, with a reaction zone thickness of 1-2mm. And there are also explosives with a rather low reaction rate, regarded as non-ideal. An example of such an explosive is ANFO = Ammonium nitrate + fuel oil.

In addition to the diameter effect test for characterizing the ideality measure or the sensitivity measure of explosives, researchers sometimes also use the thickness effect test. In this test the explosive sample is a wide slab. Similar to the diameter effect test we measure in this test the steady detonation velocity (D) as function of the slab thickness (h), and the thickness effect curve is $D(1/h)$.

Next we show that from the equations of motion in both geometries it follows that:

$$\frac{d(D)}{h(D)} = 2 \quad \text{or} \quad \frac{r(D)}{h(D)} = 1 \quad (1)$$

which means that for steady detonation in both geometries, the flow fields and detonation velocities are identical when $r=h$.

Using cartesian coordinates, and adding -D to these equations we get for cylindrical symmetry:

$$\frac{\partial \rho}{\partial t} = 0 = \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w) \quad \text{for cylindrical symmetry} \quad (2)$$

where u, v, w are the x, y, z particle velocity components, and ρ =density.

but as the x and y directions are equivalent, we get:

$$\frac{\partial \rho}{\partial t} = 0 = 2 \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial z}(\rho w) \quad \text{for cyl. symmetry} \quad (3)$$

For slab symmetry we get:

$$\frac{\partial \rho}{\partial t} = 0 = \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial z}(\rho w) \quad \text{for slab symmetry} \quad (4)$$

It follows that:

$$\begin{aligned} \frac{2}{\Delta x(\text{cyl.})} &= \frac{1}{\Delta x(\text{slab})} \\ \therefore \frac{2}{r} &= \frac{1}{\frac{h}{2}} \quad \text{or} \quad r = h \quad \text{or} \quad d = 2h \end{aligned} \quad (5)$$

From momentum conservation we get for cyl. Symmetry:

$$\rho \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right) + \frac{\partial P}{\partial x} = 0 \quad (6)$$

but $u=v$, $\frac{\partial}{\partial x} = \frac{\partial}{\partial y}$, so that $u \frac{\partial u}{\partial x} = v \frac{\partial u}{\partial y}$. It follows that:

$$\begin{aligned} \rho \left(2u \frac{\partial u}{\partial x} + w \frac{\partial u}{\partial z} \right) + \frac{\partial P}{\partial x} &= 0 \quad \text{for cyl. symmetry} \\ \rho \left(u \frac{\partial u}{\partial x} + w \frac{\partial u}{\partial z} \right) + \frac{\partial P}{\partial x} &= 0 \quad \text{for slab symmetry} \end{aligned} \quad (7)$$

which leads to:

$$2 \frac{u(\text{cyl.})}{\Delta x(\text{cyl.})} = \frac{u(\text{slab})}{\Delta x(\text{slab})} \quad (8)$$

which by using Eq. (5) leads to:

$$u(\text{cyl.}) = u(\text{slab}) \text{ at } r(\text{cyl.}) = x(\text{slab})$$

where $x = 0$ and $x = h$ are the slab boundaries. (9)

From Eqs. (5) and (9) it follows that a steady detonation wave in a rod of radius r (or diameter $d=2r$), should be the same as a steady detonation wave in a slab of thickness $h=r$.

But tests [1] show that this kind of equivalence exists only approximately for ideal explosives, and almost not at all for non-ideal explosives. To show this they measured in tests the diameter effect curve $D(1/d)$ for rods, and the thickness effect curve $D(1/t)$ for slabs (where $t=\text{slab thickness}=h$). In Figs. 1,2 and 3 we show the results obtained for these curves in [1] for the explosives: PBX9501 (ideal), PBX9502 (semi-ideal) and ANFO (Ammonium nitrate + fuel oil, non-ideal).

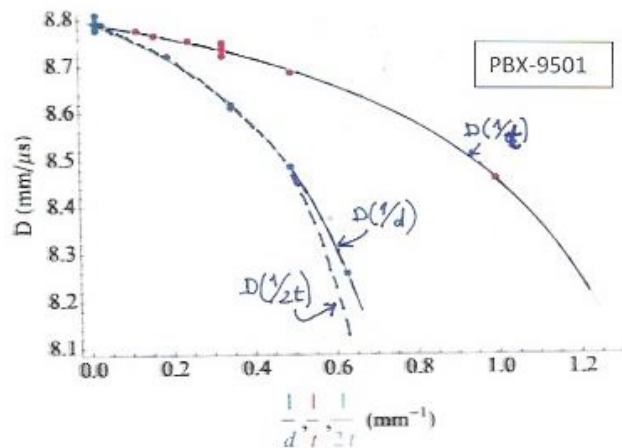


Figure 1. Diameter effect curve and thickness effect curve for PBX9501 (ideal explosive).
D=detonation velocity, d=rod diameter, t=slab thickness

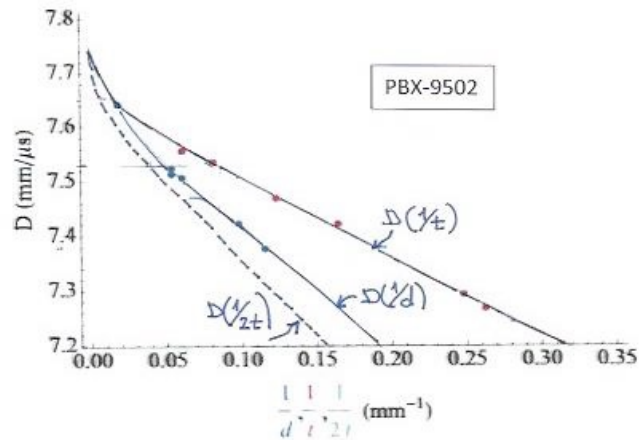


Figure 2. Diameter effect curve and thickness effect curve for PBX9502 (semi-ideal explosive).
D=detonation velocity, d=rod diameter, t=slab thickness

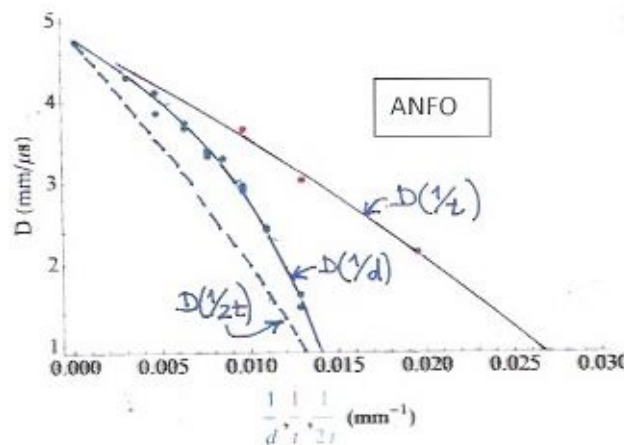


Figure 3. Diameter effect curve and thickness effect curve for ANFO (non-ideal explosive).
D=detonation velocity, d=rod diameter, t=slab thickness

Comparing the blue line $D(1/d)$ to the green line $D(1/2t)$ in the above three figures, we see that: 1) they are not equal; 2) the difference between the two lines is larger for a less ideal explosive; and 3) generally, $d(D) < 2t(D)$ (where t is the same as h that we used above). Similar results (which we don't quote here) on deviation from ideal scaling of non-ideal explosives were obtained in tests by other researchers during the years, for various explosives. In what follows we propose an explanation to those deviations.

SIMULATIONS WITH TDRR TO REPRODUCE THE SCALING DEVIATIONS

Some years ago we performed computer simulations of detonation waves in rods and slabs [2,3]. One result of those simulations was, that a thin layer near the boundary undergoes only partial reaction. This comes about because the boundary rarefaction cools the boundary layer somewhat, and reaction rate there slows down. Our TDRR reactive flow model [4-6] is able to account for this effect, because its reaction rate is temperature dependent (increases with reactant temperature). In what follows we show results of such simulations. In those simulations the rod radius is between 5 and 10mm, and the slab thickness is between 5 and

12mm. The explosive is PBX9502. The reaction is modeled without the slow part of the reaction rate [7], which is why the resulting detonation velocity curves don't quite reproduce the experimental diameter and thickness effect curves of PBX9502. Such a disagreement is acceptable here, because we're mainly interested in the boundary effect. We use a relatively crude mesh, only 10 cells/mm. To compensate for the detonation shock smear that such a crude net causes near the boundary, we hold the boundary motion for the shock passage duration, which in our computations has been 42 μ s. We show the results for PBX9502 in Fig. 4.

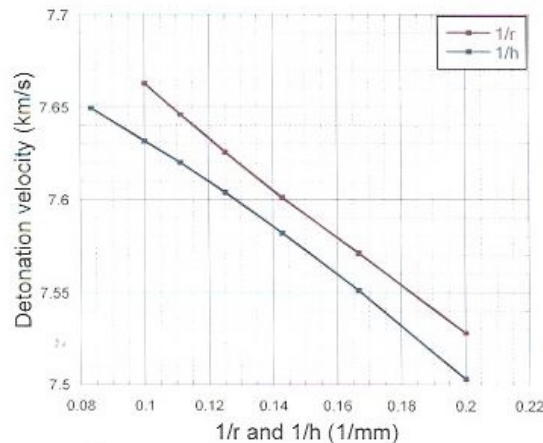


Figure 4. Radius and thickness effect curves computed for PBX9502, neglecting the slow part of the reaction rate

We see from Fig. 4 that for $D=7.53$ km/s we have $r/h=0.18/0.20=0.9$, and for $D=7.65$ km/s we have $r/h=0.083/0.108=0.78$. From Fig. 2 we have for $D=7.53$ km/s, $r/h=0.19/0.25=0.76$, and we see that the approximation is not too bad, considering our neglect of the slow part of the reaction.

In [1] they indicate that sometimes one may get in tests that $r(D)/h(D)>1$. To see when this is possible, we show next our simulation results for $r=h=10$ mm, for different values of the reaction rate equation coefficient R_T [4]. The nominal value of R_T for PBX9502 in our computations is 227/ μ s. In our computations with $r=h=10$ mm, we changed R_T between 170 and 250/ μ s. We show the results in Fig. 5.

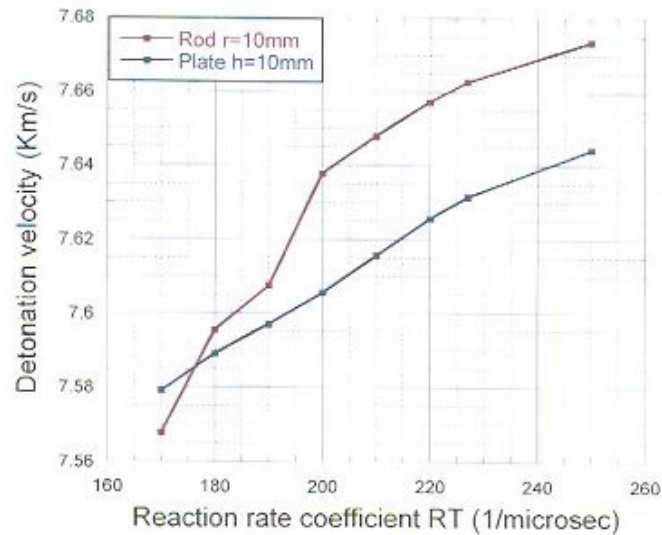


Figure 5. Steady detonation velocity in a rod of 10mm radius (red) and a slab of 10mm thickness (blue), as function of the coefficient R_T of the reaction rate equation

We see from Fig. 5 that as the reaction rate goes down (the explosive becomes less ideal), the difference between the two curves goes down as well and even changes sign, which means that we have there: $r(D)/h(D) > 1$. From the simulations we see that this is because the boundary layer in the rod is much thicker than the boundary layer in the slab.

In Fig. 6 we show maps with lines of equal W (reaction parameter) at the end of the simulation in the rod and in the slab, for the smallest reaction rate coefficient that we used, $R_T=170/\mu$ s, and for $r=h=10$ mm.

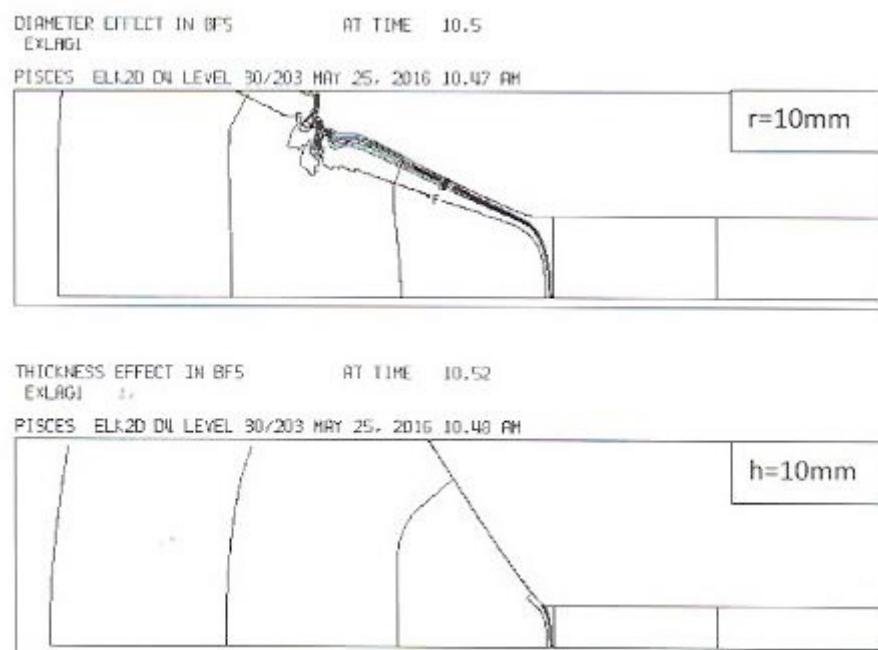


Figure 6. Maps with lines of equal values of reaction parameter (W) at the end of the simulations in the rod and slab, for $r=h=10$ mm, and $R_T=170/\mu$ s

We see from Fig. 6 that the boundary layer thickness in the rod is much larger than that in the slab, and this explains why the difference between the two curves in Fig. 5 becomes negative.

SUMMARY

It is well known that for ideal explosives steady detonations in rods (of radius r) and in slabs (of thickness h) would scale as $r(D)/h(D)=1$, where D =detonation velocity. But for less ideal or non-ideal explosives, tests show that $r(D)/h(D)$ may generally be less than 1, but sometimes also a little larger than 1. In the past we've shown that for a detonation wave propagating along a free boundary, a partially reacted boundary layer is formed. Here we suggest that this boundary layer is responsible for the above deviation from ideal scaling. We run computer simulations in rods and plates with our reactive flow model TDRR (= reactant Temperature Dependent Reaction Rate), and show how these scaling deviations come about.

References

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