

## Diameter and Thickness Effects Scaling Deviations of High Explosives

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### ABSTRACT

One way to characterize the sensitivity (or the reaction rate) of explosives is through size-effect tests. For explosive rods they are called diameter effect tests, and for explosive plates, they are called thickness effect tests. With high reaction rate explosives, different test configurations usually yield almost the same reaction rate or detonation velocity. But with low reaction rate explosives, different test configurations usually yield somewhat different detonation velocities. Following one of our previous papers [1], we propose here that those different detonation velocities result from the phenomenon of partially reacted boundary layers, that form when a detonation wave is grazing along a free boundary. In what follows we perform computer simulations to show how such a phenomenon comes about.

### INTRODUCTION

One way to characterize the sensitivity of explosives (in the sense of reaction rate), is through size effect tests. Using cylinders (rods) they are called diameter effect tests, and using wide plates they are called thickness effect tests. From the steady state equations of motion for the two configurations it can be deduced that these two test configurations scale as:

$$\begin{aligned}d(D) &= 2h(D) \\ \text{or} \\ r(D) &= h(D)\end{aligned}\tag{1}$$

where  $d$ =rod diameter,  $r$ =rod radius.  $h$ =plate thickness and the scaling hold for the same steady detonation velocity  $D$ ,

But tests on various explosives show deviations from the above scaling. Those deviations are quite small for so called ideal explosives that have very high reaction rates, or very short (of the order of few nanoseconds) reaction times. But they can be substantial for less ideal or non-ideal explosives. Tests on various explosives show, that sometimes we may get  $r/h < 1$ , and other times  $r/h > 1$ , and that deviations from perfect scaling may be as high as 10%. Searching the literature, we haven't seen any explanation of these scaling deviations. Here we attempt such an explanation. Our explanation is based on previous work of ours [1], where we show that a boundary layer of partial reaction usually forms when a detonation wave is grazing along a free boundary.

Denoting the equivalent thickness of such a boundary layer by  $\Delta r$  for a rod, and by  $\Delta h$  for a plate, we have:

$$\frac{r - \Delta r}{h - \Delta h} = 1 \quad \frac{r}{h} = 1 - \frac{2\Delta h - \Delta r}{h}$$

so that :

$$\frac{r(D)}{h(D)} < 1 \quad \text{for} \quad 2\Delta h > \Delta r \quad (2)$$

$$\frac{r(D)}{h(D)} > 1 \quad \text{for} \quad 2\Delta h < \Delta r$$

On this basis we suggest that scaling deviations of the diameter effect from the thickness effect are related to the partially reacted boundary layer phenomenon.

### SIMULATIONS

To establish the above suggestion, we ran direct numerical simulations of the rod and plate geometries, using our reactive flow code that we call TDRR (Temperature Dependent Reaction Rate) [2]. As we've shown previously, by using our TDRR model we're able to reproduce the partially reacted boundary layer discussed above. It follows, that if TDRR is also able to reproduce the above-mentioned scaling deviations as well, this would strengthen our suggestion mentioned above for the origin of those scaling deviations.

The material parameters in our simulations are those of the explosive PBX9502, but without the slow reaction component it usually exhibits. And this is probably why we're not able to reproduce diameter effect data exactly.

The rod radius in our simulations is between 5 and 10 mm, and the plate thickness is between 5 and 12 mm. We show the simulation results in Fig. 1.

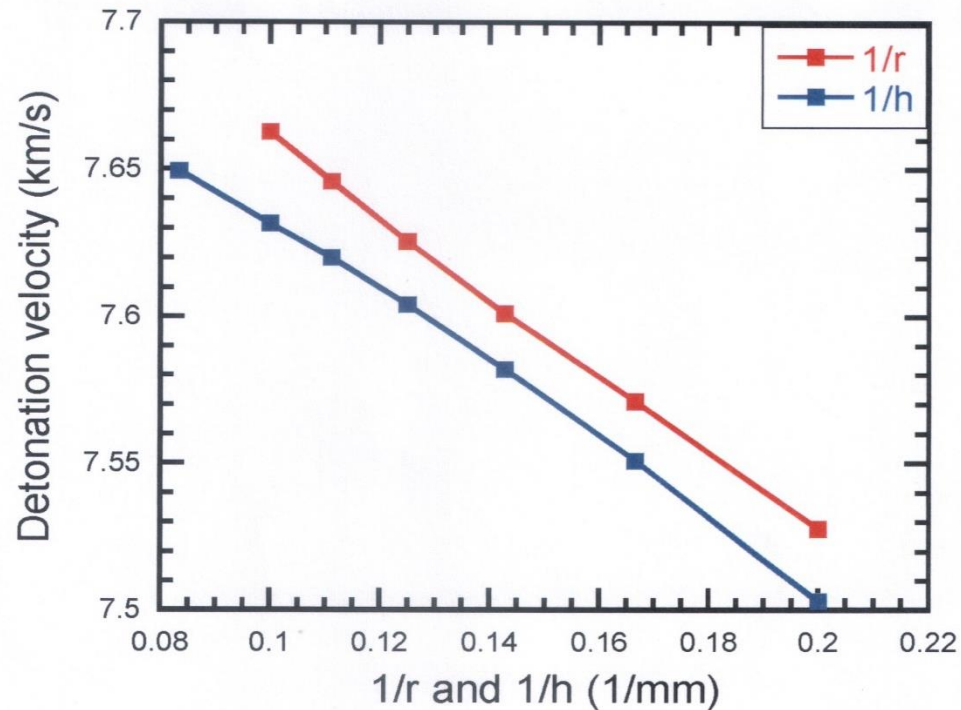


**Figure 1. Simulated radius effect and thickness effect curves for the explosive PBX9502**

We see from Fig. 1 that  $r(D)/h(D)$  is between 0.78, for the highest detonation velocity, and 0.90, for the lowest detonation velocity, which is the correct order of magnitude.

To obtain a situation for which  $r(D)/h(D) > 1$ , we ran additional simulations in which we lowered the reaction rate coefficient substantially (making the explosive less ideal). In Fig. 2 we show an example where we lowered the reaction rate by 22%. We show maps with lines of equal reaction progress parameter after 60mm into a rod of radius 10mm and into a plate of thickness 10mm.

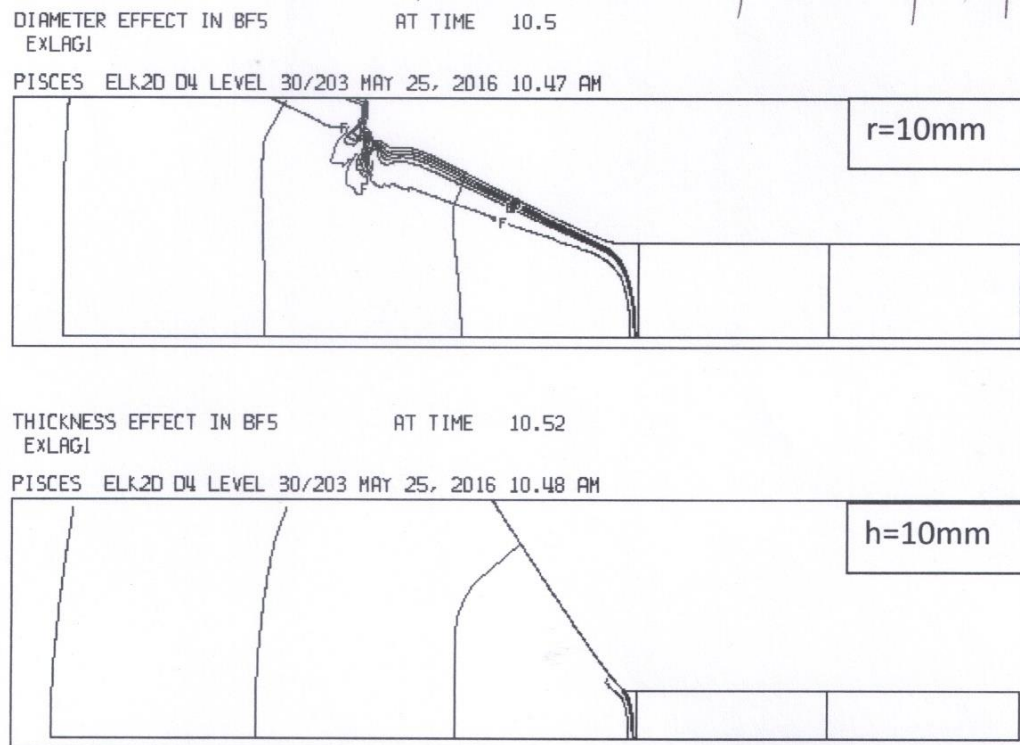


**Figure 2. Maps with lines of equal reaction progress parameter into a rod or a plate. The reaction rate has been lowered by 22% from the nominal values.**

We see from Fig. 2, that the boundary layer of the rod run is much thicker than the boundary layer of the plate run. From the equations above, this would lead to  $r(D)/h(D) > 1$ .

The nominal value of our reaction rate coefficient (which we denote by  $R_T$ ) is  $227/\mu\text{s}$ . To see how the rod-plate scaling deviation changes from  $r/h < 1$  to  $r/h > 1$ , we show the results of a series of runs in which we changed the coefficient  $R_T$  from 227 to  $170/\mu\text{s}$ , for  $r=h=10\text{mm}$ . We show the results in Fig. 3.

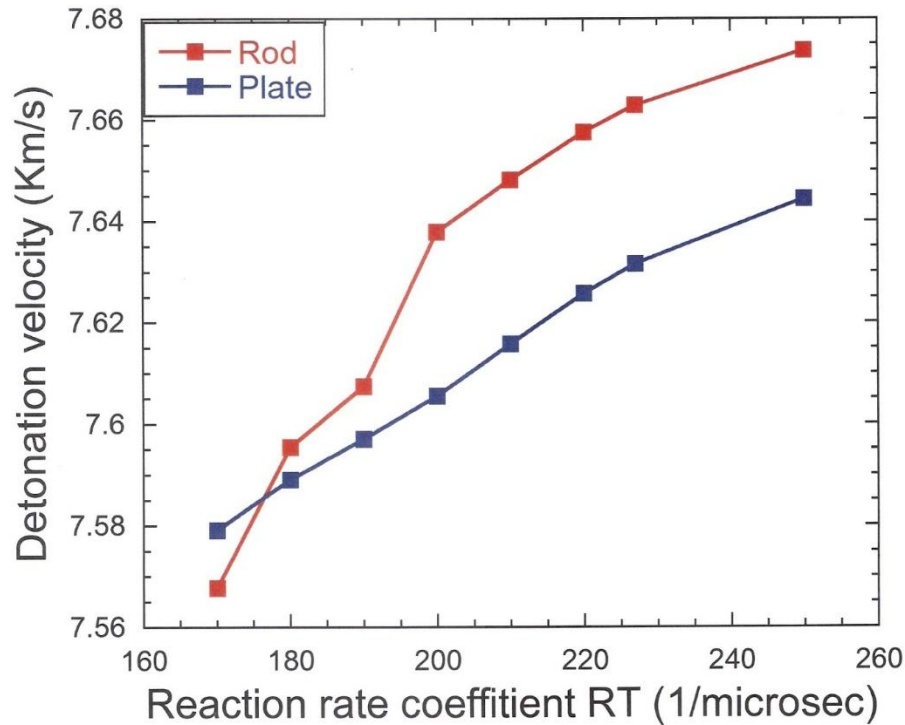


**Figure 3. Steady detonation velocity in a rod of radius 10mm (red) and in a plate of thickness 10mm (blue), when we change the coefficient ( $R_T$ ) of the reaction rate equation from 170/ $\mu$ s to 250/ $\mu$ s.**

We see from Fig. 3 that for a lower reaction rate (a less ideal explosive), the two curves get closer and eventually even cross each other. After the curves cross, we have:  $r(D)/h(D) > 1$ , and from Fig. 2 we can see that indeed, for a low reaction rate explosive, the rod boundary layer is much thicker than the plate boundary layer.

### SUMMARY

It is well known that for ideal explosives, steady detonation waves in rods (of radius  $r$ ) and in plates (of thickness  $h$ ), scale as  $r(D)/h(D) = 1$ . But for less ideal and non-ideal explosives, tests show that  $r(D)/h(D)$  may be less or greater than 1. In the past we've shown [1], 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 such a deviation from ideal scaling. We run simulations of detonations in rods and in plates with our reactive flow model TDRR, and show how these scaling deviations come about.

### References

1. Y. Partom. On the partially reacted boundary layer in rate sticks, EJAS, 11(2), 319-324 (2023).
2. Y. Partom, Hydro-reactive computations with a temperature dependent reaction rate, Shock compression of condensed matter, 460-463 (2001).