Instability of Combustion Products Interface from Detonation of Heterogeneous Explosives

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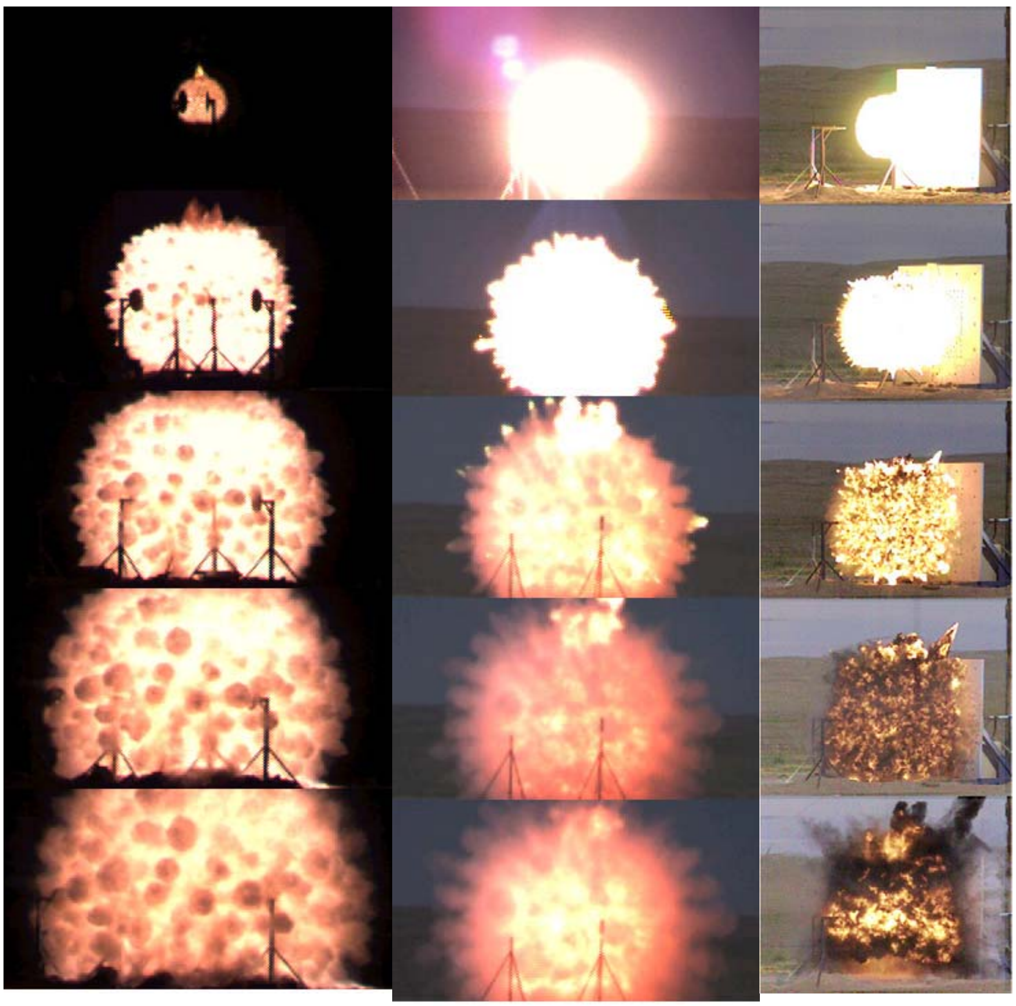
Introduction

When a condensed explosive is detonated, the resulting high-pressure gaseous combustion products rapidly expand, driving a blast wave outwards. As the combustion products expand and the pressure falls, the combustion products/air interface rapidly decelerates and it eventually attains a maximum diameter. During the deceleration of the interface, small perturbations to the shape of the interface are unstable and grow in amplitude due to the Rayleigh-Taylor instability (Taylor, 1950). For spherical charges of limited size, the interaction of the outgoing secondary shock wave, which originates as an imploding wave following the converging rarefaction in the explosion products (Brode, 1959), with the combustion products interface also destabilizes the interface due to the Richtmyer-Meshkov instability (Richtmyer, 1960; Meshkov, 1969). For heterogeneous charges containing metal particles, instabilities can also occur in the expanding particle cloud (due to particle-flow interactions) which may disturb the explosion products interface. In all these cases, the growth of the perturbations enhances the mixing with the surrounding air and hence the afterburning of the combustion products.

The development of the Rayleigh-Taylor instability on the surface of hot gases generated by an explosion has been extensively studied, particularly in the context of the detonation of gases (e.g., Ansimov and Zel'dovich, 1977), and astrophysical phenomena or focused laser experiments (e.g., Remington et al., 1999). The instability of the surface of fireballs from condensed explosive charges has been studied particularly for the afterburning explosive TNT (e.g., Kuhl et al., 1999). In the present paper, the development of instabilities on the combustion products interface will be illustrated for both homogeneous and heterogeneous metalized charges. Insight into the effect of afterburning on the interface dynamics is also provided using a simplified numerical model for the explosion dynamics.

Results

Experiments have been carried out with unconfined lightly-cased spherical charges containing both homogeneous explosives (TNT and sensitized nitromethane) and heterogeneous explosives (packed beds of metallic particles saturated with nitromethane). Details of the experimental procedure are given in Zhang et al. (2001). Figure 1 shows a series of photographs that illustrates the instability of the combustion products interface for heterogeneous charges in comparison with a homogeneous explosive charge. In both cases, perturbations are evident on the surface of the fireball at early times. However, the perturbations are more regular and persist for a longer time for the heterogeneous charges. The initial development of the interface instability for charges containing zirconium particles is illustrated in Fig. 2. The early interface perturbations can be identified at 80 μs, suggesting that these perturbations form immediately after detonation of the charge. The number of perturbations remains roughly constant after a few hundred microseconds, although the scale of the perturbations grows as the fireball expands to its maximum diameter. For the case of heterogeneous charges containing metallic particles, the surface of the expanding particle cloud can also develop nonuniformities. This is most prominent if the ignition of the particles is delayed until some time after dispersal. This is illustrated in Fig. 3 which shows the dispersal of 10 μm aluminum particles. In this case the particles form filamentary jets which subsequently ignite. As a result, the fireball exhibits a "spiky" appearance due to the remnants of the particle jets.



(a) **(b)** **(c)**

Fig. 1 Expansion of combustion products from heterogeneous (charge in Fig. 1a contained 600 – 800 μm zirconium particles, while the charge in Fig. 1b contained 100 – 200 nm Alex® aluminum powder) and homogeneous (charge in Fig. 1c contained only sensitized NM) charges. In each case the charge volume was about 1 liter. Visible in Fig. 1a are several lollipop-style pressure gauge stands, with a disk diameter of 30 cm. The plate behind the charge in Fig. 1c has a height of 1.83 m. Time between photographs for (a) and (b) is 0.5 ms, whereas the times for the photographs in (c) are 0.2, 0.4, 0.6, 1.0, and 2.5 ms, respectively.

Discussion

For the classical Rayleigh-Taylor instability analysis, the growth rate of perturbations, *n*, at a density interface (unstable if the acceleration of the interface is directed from the lighter to heavier fluid) is only dependent on the perturbation wavenumber, *k*, the acceleration, *a*, and the density difference across the interface, i.e., $n \sim (k\ a\ \Delta\rho/\rho)^{1/2}$. As a result, the growth rate increases with decreasing wavelength of the perturbations. If other physical phenomena are included in the analysis (e.g., surface tension or viscosity), then the growth of very fine scale perturbations is attenuated and the perturbation wavelength with the maximum growth rate can be predicted. The linear instability analysis is only valid at very early times, since the growth of the instability rapidly becomes nonlinear. For the metallized explosives used in the present investigation, the energy release occurs over a longer time (relative to a homogeneous explosive of the same size) due to the afterburning of the metal particles. As a result, the deceleration of the fireball is reduced and the maximum diameter of the combustion products increases. For example, the expanding fireball from the heterogeneous charge shown in Fig. 2 has a deceleration of about 5×10^5 *g*'s, whereas the deceleration of the fireball from the homogeneous charge (Fig. 1c) is several times greater. The reduced deceleration for the metalized fireballs suggests that the instability growth rate will be less than that for fireballs from homogeneous explosives (and hence the perturbations will persist longer).

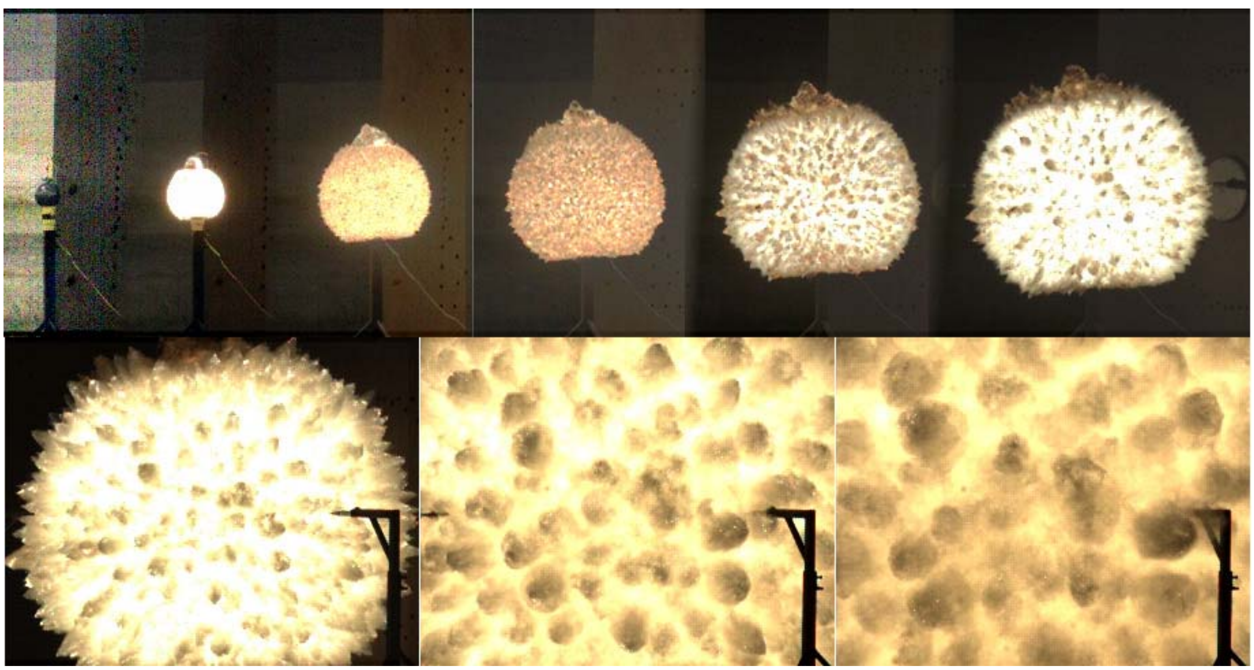


Fig. 2 Development of instabilities on fireball surface from detonation of 1 liter charge containing a packed bed of 600 – 850 μm zirconium particles saturated with NM. Times for the photographs are 0, 40, 80, 120, 160, 200, 400, 800 and 1,200 μs, respectively.

To investigate the effect of afterburning on the stability of the combustion product interface, calculations have been carried out in 1-d (spherical) and 2-d (cylindrical) geometries using Martec Ltd.'s IFSAS-II compressible-flow CFD code. The balloon analogue is used (Ritzel & Matthews, 1997) in which the energy from a 1 kg TNT charge is assumed to form a high-pressure gas volume (see Zarei et al., 2005 for more details of the calculations). Two cases are considered: i) instantaneous release of all the energy in a volume of gas, and ii) delayed release of 50% of the total energy (released uniformly within the products over a time period of 1.86 ms) to simulate the effect of afterburning of the metal particles and combustion products. Carrying out the calculation in a 1-d (i.e., spherically symmetric) geometry, the expansion of the combustion products interface, and the corresponding interface acceleration, is shown for the two cases in Fig. 4. In comparison with the no-afterburn case, when afterburn energy is included, the maximum interface deceleration (which occurs at a time of ~ 0.1 ms) is less by a factor of about 2. With afterburn, the maximum radius of the combustion products is also increased.

The effect of the interface deceleration on the development of interfacial instabilities can be illustrated by carrying out 2-d calculations for the same two cases, which are shown in Fig. 5. For the afterburning case, the perturbations that develop (the scale of the perturbations depends on the spatial resolution of the computation) are more regular than for no afterburn, consistent with the trends observed experimentally. In summary, this simplified model illustrates the qualitative effect of afterburning on the interface instability. Quantitative predictions of the instability wavelength would require multiphase model calculations including a more accurate sub-model for the temporal and spatial variation of the afterburn energy release.

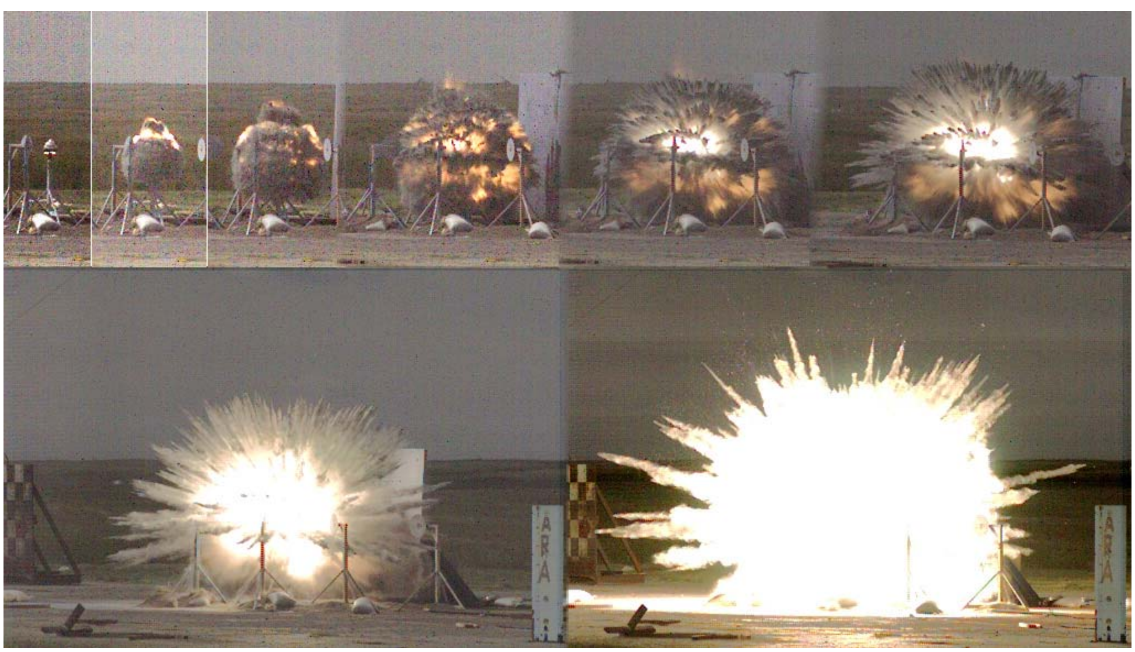


Fig. 3 Development of particle jets during the dispersal of 10 μm aluminum powder from a 1-liter charge. Times of photographs are 0.1, 0.5, 1, 2, 3, 4, 6, and 10 ms, respectively.

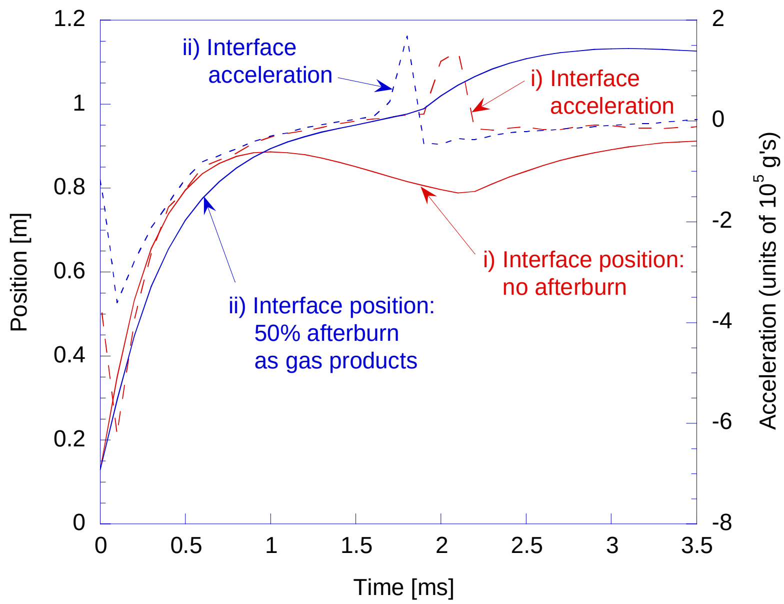


Fig. 4 Effect of afterburning on the motion of the combustion products interface. In case i) the energy is released instantaneously (no afterburn), whereas for case ii) 50% of the energy is released as afterburn.

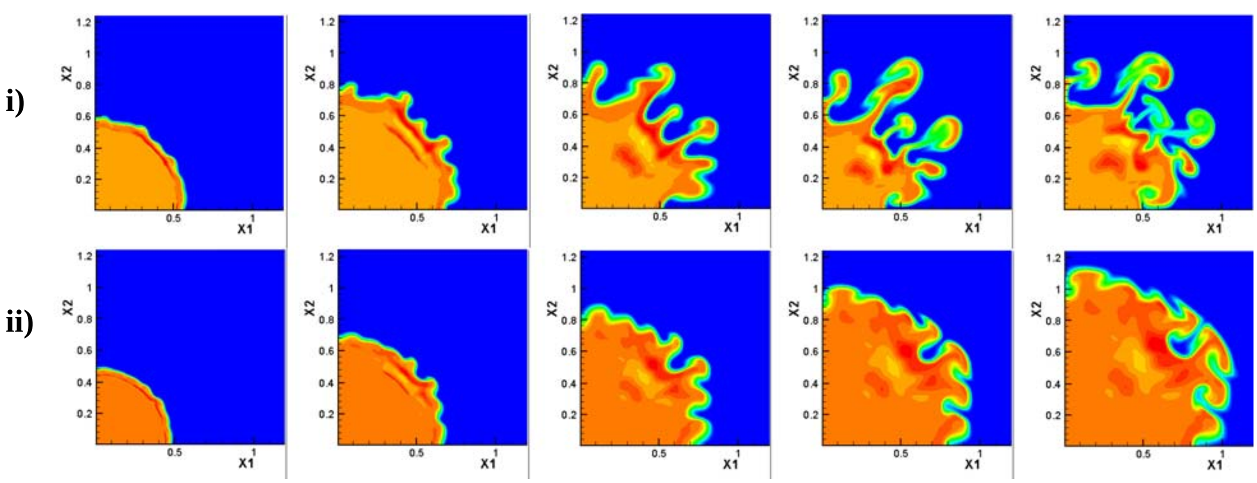


Fig. 5 Computation of the development of instabilities on the interface of a high-pressure cylindrical gas volume expanding (i) after an instantaneous energy release, and (ii) with 50% of the total energy released immediately and the remainder of the energy released within the products over several milliseconds. Times for the pictures in both cases are 0.25, 0.50, 1, 2, and 3 ms, respectively.

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