Minsk International Colloquium on Physics of Shock Waves, Combustion, Detonation and Non-Equilibrium Processes, MIC 2005, Minsk, 14-19 November 2005

Dense solid particle-fluid detonation flow

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A dense solid particle-fluid mixture consists of a *large volume fraction* of solid particles immersed in a *dense* fluid. Detonation in a liquid explosive containing a packed bed of fine metal particles serves as a good example for elucidating the fundamental problems of detonation and subsequent supersonic heterogeneous flow in a dense solid particle-fluid mixture. This paper reviews some of these problems from authors' own studies.

Theoretical models for detonation in a solid particle-fluid system have mostly been based on two-phase fluid dynamics models taking mass, momentum and heat transfer between the phases as well as dynamic particle compaction into consideration. A frozen shock interaction is often assumed in which solid particles are not accelerated as the leading shock front crosses the particles. Behind the shock front, a drag force is assumed to determine the momentum transfer between the fluid phase and the particles. While the assumption of a frozen shock interaction has proven adequate for detonation in solid particle-gas flows, it could fail for detonation in condensed matter containing metal particles when the shock-particle interaction time is comparable to the velocity relaxation time related to the drag. The liquid loses momentum during the shock-particle interaction if the reaction time of the metal particles is larger than the shock interaction time. Figure 1 shows that the post-shock velocity for aluminum particles achieved 70-80 % of the value of the shocked liquid velocity. For an explosive density from 1-1.8 g/cm^3 and a wide range of metal particles including magnesium, beryllium, aluminum, nickel, tungsten and uranium, it was found that the particle velocity after the shock crosses the particle was a strong function of the initial density ratio of explosive to metal. Momentum transfer during the shock interaction together with that behind the shock front was found to be responsible for the detonation velocity deficit observed in experiments. While the momentum loss desensitizes the detonation initiation, the shock interaction with particles also generates hot spots to increase the detonation sensitivity. Experiments showed that detonation propagated in a 48 mm PVC tube filled with liquid isopropyl nitrate (IPN) containing packed 100 nm aluminum particles, while it failed to propagate in a 310 mm PVC tube filled with the neat IPN. Depending on the choice of particles and liquid, the failure diameter of a solid particle-liquid system can be either larger or smaller than that of the liquid itself.

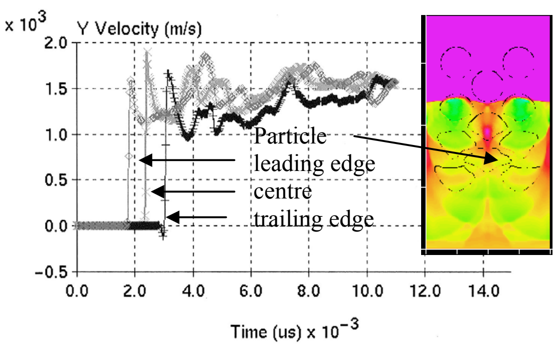
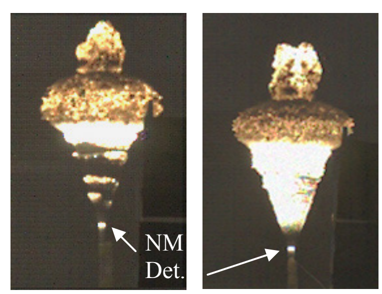


Fig. 1 Al particle velocity subjected to 101.3 kbar shock in a 1 g/cm^3 liquid-Al particle system



a) 27 mm tube b) 41 mm tube

Fig. 2 Al particle ignition in cylindrical charges of sensitized NM-packed Al particles in a glass tube

For this kind of heterogeneous system, significant metal particle combustion takes place after the liquid detonation zone if the liquid reaction time is smaller than the characteristic particle reaction time. In this case, a second critical charge diameter was identified, that is, the critical diameter for the particle ignition (CDPI) in the detonation products, in which the residence time of the particles is sufficient to heat the particles to burn and overcome the quenching effect of the unsteady expansion of the detonation products (Fig. 2). The CDPI was found to be a function of particle reactivity and morphology or size, but also of the oxidizing gases present in the detonation products. For some metal particles, there appears to exist an upper limit of CDPI, such that for charges larger than that, the energy-scaled blast arrival time, peak pressure and positive impulse collapse within a degree of scatter, regardless of the changes in particle size and shape. The scatter band is inherent to the multi-length-scale energy release process of particle combustion. For charges smaller than the upper limit of CDPI but larger than a lower limit, the particle combustion contributes to the blast in various extents.

By choosing the solid particles and liquid, the momentum and heat loss from the liquid and its detonation products to the particles can be regulated within the detonation zone to satisfy the necessary conditions for a weak detonation solution, while various solutions can be realized by controlling the late particle reaction to meet the rear flow conditions behind the detonation zone. In related experiments, in which particles were dispersed in a tube containing a combustible gas which was then detonated, two types of double-front weak detonation waves were identified. The type-I solution was characterized by a two-shock structure where the second shock behind the detonation zone has the same velocity as the leading shock. In the type-II solution, the second shock receded from the detonation zone to produce an ever-widening region of uniform supersonic flow between the end of the detonation zone and this shock (Fig. 3). The two types of weak detonation waves can propagate in micrometric aluminum powder dispersed in detonation products with the presence of oxygen, water vapor, carbon dioxide, but propagation is unlikely in detonation products dominated by carbon monoxide. By decreasing the heat release rate of particles, the type-I double-front detonation was changed to the type-II detonation, in which the second shock recedes with weaker shock strength with a further decrease in the heat release rate of particles.

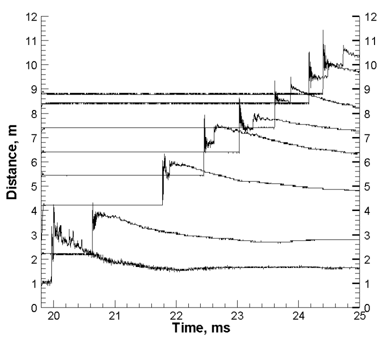


Fig. 3 Type-II double-front detonation

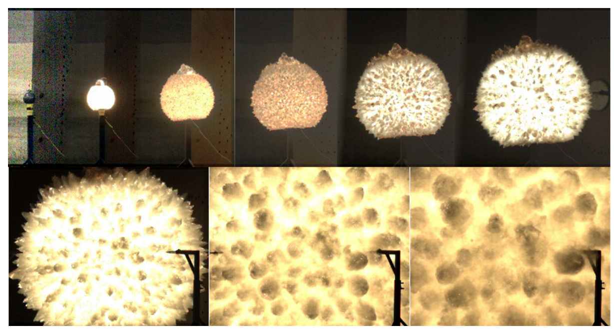


Fig. 4 Fireball surface instability from a 1-L charge of sensitized NM and packed zirconium particles

When the detonation reaches the edge of a solid particle-liquid charge, the resulting gaseous detonation products rapidly expand, driving a blast wave outwards with the deceleration of the interface between the high-density detonation products and the low-density air. This results in the Rayleigh-Taylor instability at the interface. The growth rate of the classical Rayleigh-Taylor instability at a density interface depends on the perturbation wavenumber, the acceleration of the interface directed from the lighter to heavier fluid, and the density difference across the interface. For liquid charges containing metal particles, the energy release occurs over a longer time with respect to a homogeneous explosive of the same size due to the afterburning of the particles. As a result, the deceleration of the interface is reduced and the maximum size of the combustion products increases. The reduced deceleration suggests that the instability growth rate will be less than that for homogeneous explosives. Hence, the perturbations were found to be more regular and persist longer (Fig. 4), while the scale of the perturbations grew as the fireball expanded. Furthermore, the surface of the expanding particle cloud can also develop nonuniformities due to particle-flow interactions. This was most prominent if the ignition of the particles is delayed until some time after detonation. In this case the particles formed filamentary jets which subsequently ignite. In all these cases, the growth of the perturbations enhances the mixing with the surrounding air and hence the afterburning of the combustion products.

Since a portion of the energy released during the detonation of the liquid is transferred to the kinetic energy of the particles, the effect of particle momentum must also be considered in the near field of the blast wave, particularly for relatively large particles. Experiments using cantilever gauge measurements clearly indicated that for the same liquid charge mass, the strains and final bend angles of the cantilevers were amplified by a factor of 3-4 out to a range of 15 charge radii when inert metal particles are present in the charge. The loading amplification is proportional to the integrated particle momentum flux (i.e., the area under the curve of $\rho_p v_p^2$ which is 3-4 times the area under the curve of $\rho_g v_g^2$). The effect of particle momentum was also observed in experiments using reactive particles. Hence, the near-field total impulse for the heterogeneous blast must be defined as the sum of the gas total impulse and the integrated particle momentum flux.