Interfacial Instabilities in Explosive Gas-Particle Flows

David L. Frost[1], Yann Gregoire[2], Samuel Goroshin[1], and Fan Zhang[3]

[1]McGill University
Montreal, Quebec, Canada

[2]Institut Pprime, ENSMA,
Futuroscope-Chasseneuil, France

[3]Defence R&D Canada – Suffield
Medicine Hat, Alberta, Canada

1 Introduction

When a group of particles is rapidly accelerated by interacting with a shock or expansion wave and subsequent high-speed gas flow, instabilities typically develop within and at the surface of the particle cloud. For example, Anilkumar et al. [1] observed the motion of packed beds of particles within a vertical shock tube accelerated by the interstitial gas following depressurization. They found that during acceleration, the flow was highly inhomogeneous with large fluctuations in both velocity and density. During the initial acceleration phase, the particle bed fractured into layers or slabs. The bottom surface of the layers became unstable in a fashion analogous to the Rayleigh-Taylor instability, forming bubbles within the expanding particle cloud. At later times, filamentary particle structures were observed.

Instabilities may also develop when a layer of particles is accelerated by a shock from a condensed explosive. In this case, instability of the top surface of the particle layer may lead to the formation of particle clusters or jets. This has been observed following the detonation of enhanced blast explosives containing metal particles [2] and during the breakup of liquids and particle beds used for blast mitigation [3]. In the latter study, Milne et al. [3] found that the particle jets they observed at later time form at the very earliest stages of particle dispersal. From a consideration of the timescale of the development of the particle jets, they concluded that the classical Rayleigh-Taylor instability growth rates were too slow to explain the observations, although an alternative model for the jet formation was not proposed.

Explosive particle dispersal typically occurs in one of two configurations: i) a uniform mixture of the particles with the explosive, or ii) a stratified arrangement with the particles surrounding a homogeneous explosive charge. Zhang et al. [4] observed the formation of jets during the dispersal of either liquid fuel, dry small Al particles, or a hybrid mixture of the same liquid and Al particles, using cylindrical charges with a central burster charge. They observed a different shape of jets for the three cases. The number of jets is similar for the liquid and hybrid mixture cases in the early dispersal, while the number of jets for the dry powder case is smaller. The dry powder produced the most stable jets, particularly in contrast with the pure liquid, in which case aerodynamic breakup and evaporation of the droplets limited the radius of dispersal.

Correspondence to: david.frost@mcgill.ca

The present experiments were carried out to investigate the susceptibility of packed beds of particles to develop surface nonuniformities during explosive loading. Of particular interest is the dependence of the formation of instabilities at the surface of the particle bed on the particle properties, e.g., particle size, density, morphology, and the rate at which they are accelerated, which depends on the relative mass of the particle layer and explosive charge. The experiments were conducted in both spherical and conical geometries, with the primary diagnostic used being high-speed video photography. The experimental results will first be presented, followed by a discussion of the physical mechanisms that may lead to instability of the surface of the particle layer.

2 Experimental Methodology

The experiments in the present investigation were carried out in two different geometries. In the first, a packed bed of particles was contained within a thin-walled glass sphere. The particles were dispersed with a centrally located spherical booster charge of C4 with a mass ranging from 15 to 100 g. To eliminate the effects (if any) of the breakup of the charge casing on the particle dispersal, a second charge configuration was used in which the particles were placed within a vertically-oriented conical funnel. This ensures a free surface for the powder and approximately simulates the expansion of a sector of a stratified spherical charge of powder surrounding an explosive charge. The funnel is held in place with a cardboard tube. To reduce the rate of side expansion of the powder, the space between the funnel and tube was filled with a packed bed of fine (~1 mm dia) sand. The cone diameter was 16.5 cm with a cone angle of 60°. The C4 charge (between 15 and 80 g) was placed within a plastic sphere at the apex of the cone and initiated with a detonator placed into the C4 from below.

Three different types of particles were used in the tests: iron, aluminum and magnesium. The specifications of the powders used are as follows: 2 sizes of iron powder (FE-110, Atlantic Equipment Engineers, NJ, 32±15 μm dia, solid volume fraction of packed bed 60%; Ferrospheres, Draiswerke, NJ, 275±25 μm dia, solid fraction 61%), 2 sizes of spherical aluminum powder (H-10, Valimet, CA, 13±10 μm dia, solid fraction 57%; H-95, Valimet, CA, 114±40 μm dia, solid fraction 60%) and one size of spherical magnesium powder (GRAN 17, Reade, PA, 240±60 μm dia, solid fraction 63%).

3 Experimental Results

The explosive dispersal of fine (32 μm) iron powder is illustrated in Fig. 2. The jets are formed at very early times and are visible within a few hundred microseconds. The jet structure is quite uniform and the number of jets appears to remain roughly constant as they move radially outwards at high speed. The angular spacing of the jets is difficult to determine, but if we consider a horizontal plane through the center of the particle cloud, the average angular spacing of the jets can be estimated to be about 3±1°.

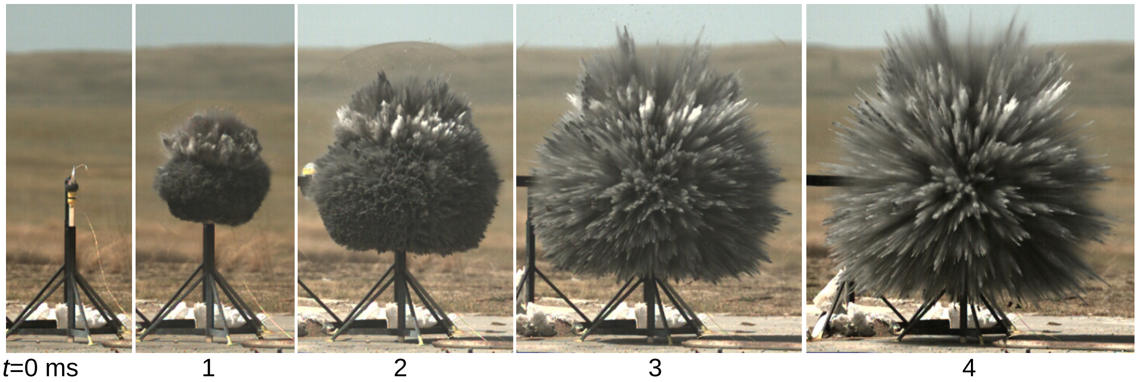

Fig. 1 Explosive dispersal of a packed bed of 978 g of 32 μm iron particles. Average velocity of the particle front over the first millisecond was 375 m/s.

When fine (13 μm) aluminum particles were explosively dispersed in the conical arrangement, the surface of the particle bed was very unstable and quickly developed jet structures, as shown in Fig. 2. The jets move in a ballistic manner, with particles shed from the outer surfaces of the jets. The jets are quite stable and maintain their integrity for 10's of milliseconds. The fine sand particles surrounding the explosive charge are also explosively dispersed in a lateral direction. The cloud of sand particles initially forms a cellular-like structure (see photograph at 3.23 ms). After several milliseconds, the sand "cells" coalesce to form individual ballistic sand jets. The scale of the instabilities that develop on the surface of the sand cloud and the number of sand jets that develop is a function of the velocity of the sand; as the explosive charge mass is increased, increasing the velocity attained by the sand, the perturbation scale decreases.

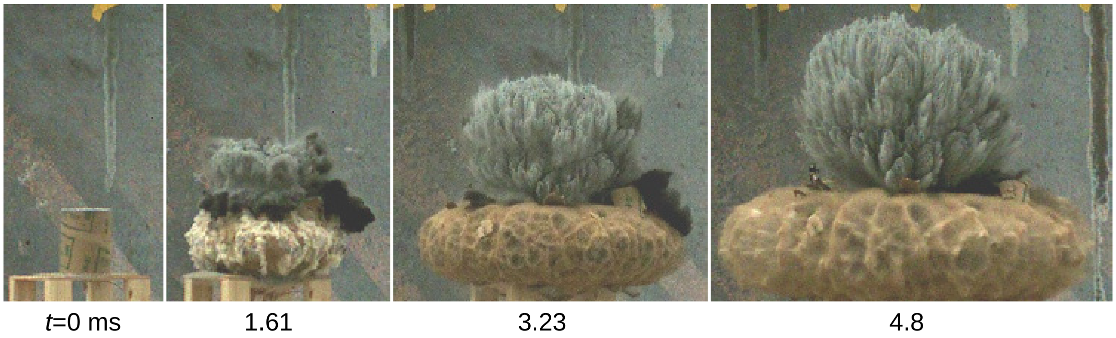

Fig. 2 Explosive dispersal of 13 μm aluminum particles. The average velocity of the surface of the particle bed over the first few frames was about 100 m/s.

When large (240 μm), spherical magnesium particles are accelerated to relatively low speeds, the surface of the particle cloud may develop an incipient instability that saturates prior to the formation of distinct particle jets. This behavior is illustrated in Fig. 3 and is repeatable – another trial with the same conditions produced nearly identical surface perturbations. In both trials, the magnesium particles spontaneously ignited after about 3 – 5 ms and the flame propagated throughout the particle cloud.

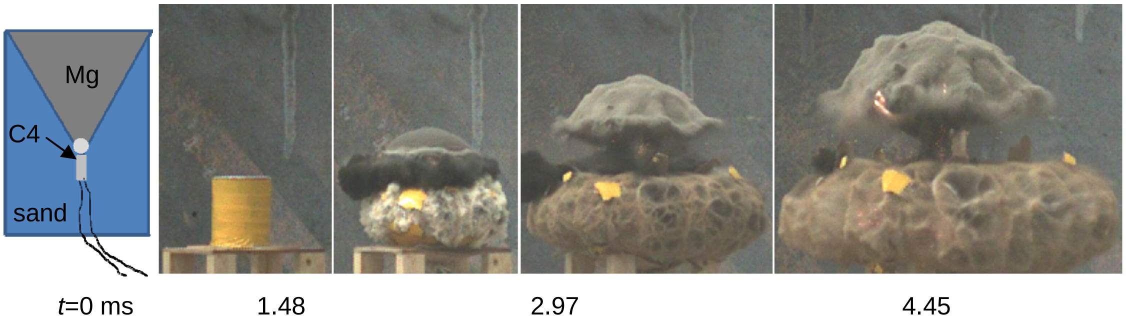

Fig. 3 Schematic of charge and high-speed images showing explosive dispersal of 240 μm magnesium particles. The average velocity of the surface of the particle bed over the first few milliseconds was about 85 m/s.

If the experiment shown in Fig. 3 is repeated, only with a larger explosive charge mass, the velocity attained by the particles is increased, and fine-scale perturbations develop on the surface of the particle bed which develop into widely spaced jet structures. Experiments were carried out with various combinations of particle density, size and explosive mass. Three different morphologies of the structure of the surface of the particle cloud were observed: i) unstable, ii) marginally stable and iii) stable. In the next section, an attempt will be made to correlate the different behaviours observed with the various experimental parameters.

4 Discussion

When packed beds of metallic particles are explosively dispersed, the surface of the expanding particle cloud develops one of a variety of structures. For a particle layer that is accelerated to a low speed, the surface of the particle cloud remains smooth. With an increase in velocity, incipient instabilities develop on the surface, forming filaments consisting of clusters of particles. At higher speeds, the particle cloud is highly perturbed and coherent jet structures form. Several questions are immediately raised: What is the mechanism(s) for the formation of these instabilities/jets? How does the number or scale of the jets depend on the charge and flow properties (e.g., particle size and density, $m_{\text{particles}}/m_{\text{explosive}}$, velocity, etc.)?

A number of different mechanisms may lead to the formation of particle jets. Once formed, aerodynamic forces tend to stabilize the jets as they propagate over large distances. Consistent with the earlier work of Milne et al. [3], an important observation is that the incipient jet structure occurs very early during the expansion of the particle bed and that the number of perturbations observed at early times on radiographs was essentially the same as the number of particle jets observed in late time videos. Hence the instability likely develops during the early motion of the dense particle bed following the propagation of the initial shock and expansion wave reflected from the bed surface.

Following the work of Grady [5,6] on the fragmentation of condensed matter, it seems reasonable to postulate that the breakup of a layer of particles at high strain rates is also governed by a balance of inertial effects tending to fracture a layer of particles versus viscous dissipation which will tend to maintain the stability of the layer. The ratio of inertial forces to viscous forces during the shock compaction of particle layer may be referred to as the particle compaction Reynolds number, Re, and may be defined as $\text{Re} = \rho UL/\mu_c$, where ρ, U, L, and μ_c are the density, velocity, characteristic length (e.g., layer thickness), and effective particle compaction viscosity of the layer, respectively. The compaction viscosity is difficult to determine since it depends on the interparticle forces during the process, which will depend on the particle properties and particularly on the particle morphology. Baer and Nunziato [7] considered the dynamic compaction process of a granular material and proposed the following approximate expression for compaction viscosity, μ_c, based on a simple transport model analogous to that found in the kinetic theory of gases: $\mu_c \sim \gamma_s c_s d_s$, where γ_s, c_s, and d_s are the particle mass density, solid-phase sound speed, and mean particle diameter, respectively, following the notation in [7]. Combining this expression with the definition of Reynolds number, gives the following expression for the particle compaction Reynolds number: $\text{Re} = (\rho UL)/(\gamma_s c_s d_s)$.

Based on the arguments in the previous paragraph, it is of interest to see how the stability of the surface of the particle layer depends on the compaction Reynolds number. Based on the photographic records, for the cases where particle jets develop, an estimate has been made of the angular spacing of the jets, θ_{jet}, for a cross-sectional plane through the center of the dispersed particle clouds. Rather than counting the number of jets explicitly, we note that the total number of jets for a spherically symmetric charge will be proportional to $4\pi/\theta_{\text{jet}}^2$. These estimated values are plotted as a function of the Reynolds number for the current experiments in Fig. 4. The velocity used in the Reynolds number was the particle velocity determined at early times (typically during the first millisecond) and noted on previous figure captions. The length L was taken to be the thickness of the particle layer.

In general, the number of jets increases (i.e., the jet spacing decreases) with increasing compaction Reynolds number. For the metallic particles, there appears to be a threshold Reynolds number (between 1 and 10) for which incipient instabilities begin to form on the surface of the particle layer. Above this threshold value, particle jetting is observed. For the iron particles, below a Reynolds number of 1, the surface of the particle cloud was stable. For a given Reynolds number, the number of jets formed depends on the type of particle, possibly due to the variation in the particle morphology from one type of particle to the other.

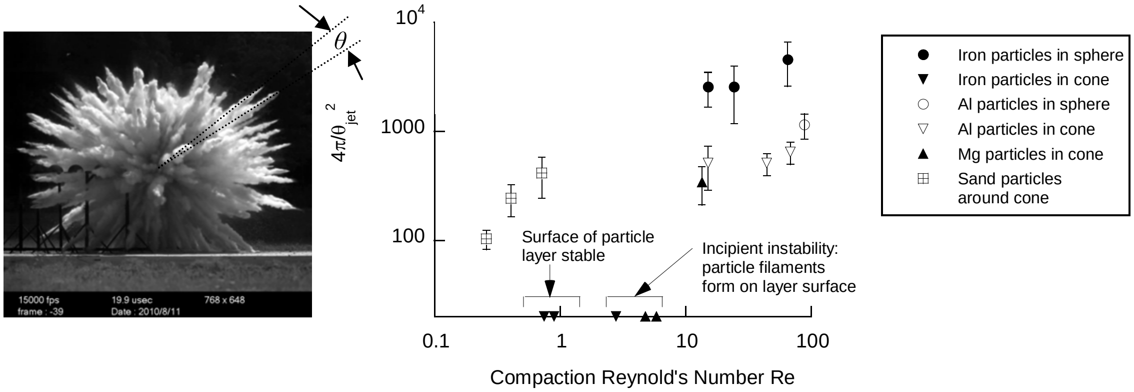

Fig. 4 Dependence of $4\pi/\theta_{\text{jet}}^2$ (which is proportional to the total number of jets for a spherically symmetric charge), where θ_{jet} is the angular spacing of adjacent particle jets, on the compaction Reynolds number governing the ratio of particle inertial to particle viscosity effects.

5 Simulations

To explore qualitatively the dependence of jet formation on various parameters, preliminary simulations have been carried out based on the smoothed particle hydrodynamics (SPH) method computed using the LS-DYNA code. SPH is a mesh-free Lagrangian method originally developed for modeling astrophysical phenomena. SPH modeling provides several advantages, for example, it can handle large deformations and density variations and no calculation time is wasted on empty regions. Simulations were carried out for the explosive dispersion of a particle bed in air, under different charge geometries and explosive/particles mass ratios. The sample calculation shown in Fig. 5 illustrates the capabilities of LS-DYNA and SPH modeling. Three adjacent planar layers were considered: a bottom explosive layer (nitromethane, 2.5cm thick, denoted by the red particles), a layer of glass particles (2.5cm thick, denoted by the blue particles) and a surrounding air layer (10 cm thick, green particles). For this 2D simulation, 15000 nodes were used. The explosive is initiated at a point on the bottom of the layer at its center and the detonation wave propagates radially and transmits a shock into the particle layer (second frame in Fig. 5). As the particles are initially accelerated, the particle front is rather smooth and uniform. However, as the particles move into the air layer, the top layer of particles becomes perturbed with some particles penetrating into the air, inducing strong deformations in the air layer (last frame in Fig. 5). These preliminary calculations suggest this method may be useful for investigating jet formation. However a variety of different configurations must be studied and compared with experimental results to determine whether or not this method can shed light on the physical mechanisms that govern jet formation.

5 Conclusions

Explosive dispersal of particles often leads to the formation of a “spiky” particle cloud consisting of a number of particle jets that remain stable after travelling for many jet diameters. Experiments with a range of different particle sizes and densities, and particle and explosive charge masses show that the stability of the surface of the accelerated particle layer correlates with the ratio of inertial to viscous forces acting on the particle layer during the compaction and initial expansion stages. The instability that forms on the surface of the particle layer following shock loading occurs at very early times and subsequent growth and propagation of the jets is subject to aerodynamic forces. Obtaining a more mechanistic description of the shock fracturing of a packed bed of particles will likely require detailed mesoscale computations that address the particle-particle interactions that play an important role in dense gas-particle flows.

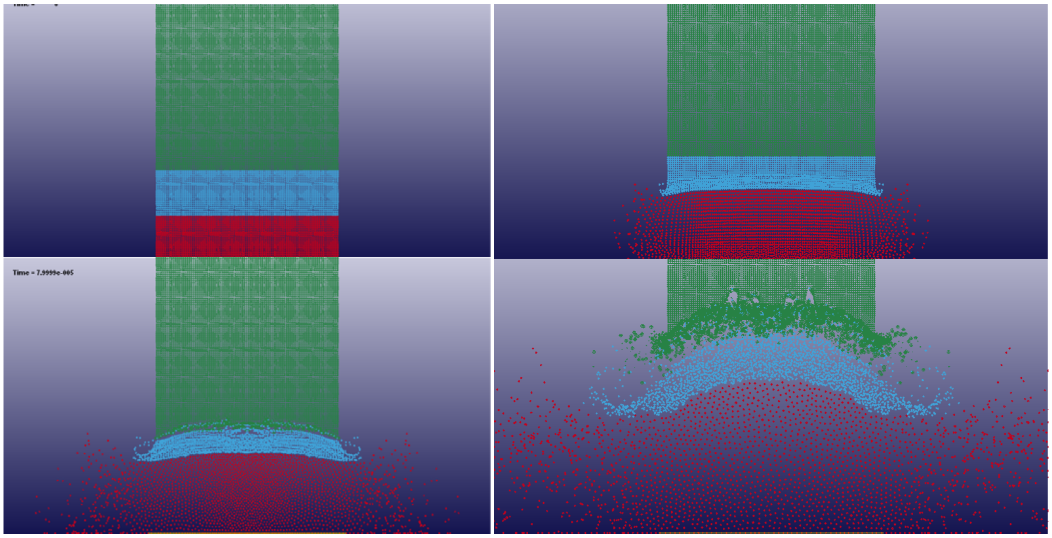

Fig. 5 Dispersal of glass particles (blue layer) into air (green particles) following the detonation of an explosive nitromethane layer (red particles), computed using the SPH method. The detonation is initiated at a point at the bottom of the nitromethane layer, in the middle of the layer.

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References

[1] Anilkumar AV, Sparks RSJ, Sturtevant B. (1993). Geological implications and applications of high-velocity two-phase flow experiments. J. Volcanology Geothermal Res. 56: 145.

[2] Ritzel DF, Ripley RC, Murray SB, Anderson J. (2007). Near-field blast phenomenology of thermobaric explosions. Proc. 26th Int. Symp. Shock Waves, Göttingen, Germany.

[3] Milne AM, Parrish C, Worland I. (2010). Dynamic fragmentation of blast mitigants. Shock Waves 20: 41.

[4] Zhang F, Yoshinaka A, Ripley R. (2010). Hybrid detonation waves in metalized explosive mixtures. Proc. 14th Int. Detonation Symp. Coeur d'Alene, Idaho.

[5] Grady, DE. (1982). Local inertial effects in dynamics fragmentation. J. App. Phys. 53: 322.

[6] Grady, DE. (1988). The spall strength of condensed matter. J. Mech. Phys. Solids 36(3): 353.

[7] Baer, MR, Nunziato, JW. (1986). A two-phase mixture theory for the deflagration-to-detonation transition (DDT) in reactive granular materials. Int. J. Multiphase Flow 12(6): 861.