Explosive formation of coherent particle jets

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Abstract. A coherent jet of particles may be generated by accelerating a conical volume of particles by detonating a layer of explosive lining the outside of the cone. Experiments have been carried out to determine the dependence of the velocity history and coherency of the jet on the particle properties and the ratio of the masses of the particles and explosive. Steel particles form thin, coherent jets, whereas lighter glass particles lead to more diffuse jets. For steel particles, the cone angle had little effect on the coherency of the jet. The efficiency of the conversion of chemical to kinetic energy is explored by comparing the experimental jet velocity with the velocity predicted from a formulation of the Gurney method for a conical geometry. The effect of particle density and cone angle on the jet formation and development was also investigated using a multimaterial hydrocode. The simulations give insight into the extent of the deformation of the particle bed in the early stages of explosive particle dispersal.

1. Introduction

A high-speed jet of material can be formed with a shaped charge in which a volume of explosive accelerates a conical liner surrounding a hollow region [1]. Under the high pressures of the explosive, the liner flows hydrodynamically to form a continuous jet of material. If the conical volume is filled with a bed of loosely-packed particles, a jet of particles may be formed in a similar manner by detonating an explosive layer surrounding the conical volume. The dependence of the properties of the jet formed in this manner (e.g., jet velocity, diameter) on the properties of the particles (e.g., diameter, density) and the charge (e.g., relative masses of the particles and explosive, cone angle) are currently not known.

A common technique for estimating the velocity of inert material accelerated by the detonation of an explosive was first proposed by R. W. Gurney [2]. By making several approximations, a so-called Gurney velocity may be derived which depends, for a given explosive, only on the explosive and inert material masses for a given geometry. This method is typically applied to estimating the velocity of inert fragments from a solid spherical or cylindrical casing surrounding a high explosive. Frost et al. [3] applied the Gurney method to the acceleration of a conical volume of material supported by a cylindrical volume of tamper material. They derived a Gurney velocity for this geometry with the assumption that the powder and tamper material move along the same axis, the density of the gases remains spatially uniform, and the spatial velocity distribution is linear [3].

The motivation for the present experiments was to determine the influence of the particle and charge properties on the development of the particle jet. The primary diagnostic used was
high-speed photography and the experimental jet velocities are compared with the predicted Gurney velocities. The transmission of the shock wave into the particle bed at early time is explored computationally using a multimaterial hydrocode.

2. Experimental

The experiments in the present investigation were carried out using conical charges containing packed beds of dry particles with a free surface. The charge geometry is shown in figure 1. A 0.25–mm–thick copper sheet was used to construct cones with an angle of either 45°, 60°, or 90°. Either one or two layers of a 3–mm–thick layer of Detasheet™ explosive (explosive content 63% PETN, 8% NC) were placed on the inner surface of the cone, with a small quantity of C4 (~10 g) placed at the cone apex for initiation of the Detasheet™ with a detonator inserted into the C4 from below. The cone was lightly tamped by surrounding the cone with sand, held together with a cardboard tube and thin PVC plates, as shown in figure 1. The dispersal of two types of particles was investigated: i) 463±38 μm cast steel particles, denoted ferrospheres, from Draiswerk (NJ), and (ii) 325±75 μm spherical glass beads (Potters Ballotini® impact beads). The development of the jets was visualized with Phantom 7.3 and 710 video cameras, operated at framing rates between 10,000 and 20,000 frames/s.

3. Experimental Results

3.1. Steel particle jets

The first series of experiments investigated the effect of cone angle on the development of the particle jet for steel particles. Single frames from one of the high-speed cameras documenting a trial for a cone angle of 60° are shown in figure 2. For each of the cone angles used, the detonation of the Detasheet™ explosive generated a narrow, coherent vertical jet that maintained a constant width over a travel distance of several 10’s of meters. The maximum diameter of the jet, estimated from the photographs, was about 5±1 cm. The jets produced with the larger angle cones were slightly more coherent than the smallest angle (45°), which developed some perturbations along the length of the jet axis at later times.

The time-distance trajectory of the leading tip of the steel particle jet is shown on the left in figure 3. The velocity of the jet tip is determined from consecutive points on the trajectory plot. The jet is initially obscured by the combustion products from the explosive and hence the jet velocity at very early times cannot be determined. When the jet is first visible after travelling...
Figure 2. Photographs showing the explosive dispersal of steel particles (top) and glass particles (bottom) with conical charges with 60° cone angles. Mass ratio of particles to explosive is about 19 and 7 for the steel and glass particles, respectively. For each case, the time between consecutive photographs shown is 10 ms.

about 2 m, the jet tip velocity averaged over this distance was a little more than 200 m/s. The velocity of the center of mass of the steel powder will be less than the tip velocity since the powder jet elongates as it travels, and hence the distance between the jet tip and the center of mass increases with time.

3.2. Glass particle jets

Figure 2 also shows the formation of a jet of spherical glass particles explosively dispersed with a 60° cone. The jet is considerably wider than a corresponding steel particle jet and consists of several jets that alternate in terms of which one is in the lead. Fragments are visible emerging from some of the jet structures as the jets slow, suggesting that fragments of compacted glass particles are formed during the initial particle compaction stage. The trajectory of the jet tip and estimated average jet tip velocity are shown on the right in figure 3. The glass particles accelerate to a higher speed than the heavier steel particles, but also decelerate more rapidly, presumably due to the greater drag on the more diffuse jet.
Figure 3. Trajectories of the leading edge of explosively dispersed jets of steel particles (on the left) and glass particles (on the right), corresponding to the trials shown in figure 2. The curve fits to the trajectories are second order polynomial fits. Velocity values shown correspond to the velocity between adjacent points on the trajectories. Curve fits to the velocity data correspond to a linear fit (for the steel particles) and a power-law fit (for the glass particles).

4. Numerical Results and Discussion
The acceleration and deformation of the conical volume of particles was investigated numerically using the EDEN hydrocode, which is an extensively validated multimaterial code [4]. The numerical technique utilizes a Lagrangian step followed by an Eulerian remap.

The present calculations assume a two-dimensional (z–r) axisymmetric geometry and include the conical volume of particles, the conical layer of Detasheet™ explosive and the sand surrounding the charge (the thin copper layer between the sand and the Detasheet™ is not modeled). A P-α equation of state was used to model the compaction of the particles and a programmed burn model was used for the Detasheet™. A rigid boundary condition was applied at z = 0, whereas transmissive boundary conditions were used for the other boundaries. Bulk densities for the steel and glass particles were taken to be 4.873 g/cm³ and 1.550 g/cm³, respectively.

Figure 4 shows the results for the deformation of a 90° cone of steel particles at early times after detonation of the Detasheet™. The ratios of particle to explosive masses used (44 for steel particles and 12 for glass particles) were about twice the values corresponding to the experiments shown in figure 2. The bulk of the steel powder maintains its integrity with some deformation of the surface of the particle layer occurring due to spall. At later times, the volume of particles expands along the z-axis, and contracts in the radial direction, forming a jet with a similar width as observed experimentally. The computational results for cone angles of 45° and 60° were qualitatively similar to the 90° case.

For glass particles, figure 4 shows that the converging shock and Mach stem that propagate in the particle bed generate a spatially nonuniform particle density field in the expanding particle cluster. The shock-accelerated particles form a central vertical jet with the trailing particles in the shape of a hollow shell. The shock-particle interaction near the cone apex generates cm-scale compacted glass fragments which are often recovered following a test. The formation and subsequent fracture of these fragments is not accounted for in the computations and represents another mechanism for reducing the jet coherency.

Figure 5 shows a comparison between the Gurney velocities in spherical and conical geometries with experimental jet tip velocities, as a function of particle to explosive mass ratio. The trend of increasing velocity with decreasing mass ratio predicted from the Gurney model is observed.
Figure 4. EDEN hydrocode calculations showing color map of particle and gas density (in $kg/m^3$) during early time acceleration of a conical volume ($90^\circ$ cone angle) of steel particles (on top) and glass particles (on the bottom). Diameter of the base of the cone is 16.5 cm. Times of frames shown are 0, 50, 100, 200, 300, 400, and 500 $\mu$s.

Figure 5. Gurney velocity ($V_M$) for a spherically symmetric charge (solid line) in comparison with the Gurney velocity for a conical charge (solid symbols), plotted for the particle to explosive mass ratios corresponding to the experimental conditions. The experimental velocities (open symbols) plotted correspond to the peak velocity of the head of the particle jet.
experimentally, although there is some discrepancy between the predicted and measured particle velocities. A more accurate validation of the predicted Gurney velocities would require the use of flash radiography to determine the mean velocity of the particle volume at early times when the particles are obscured visually by the opaque combustion products.

5. Conclusions
The present experiments have shown that a configuration in which a conical volume of particles is accelerated with a layer of Detasheet™ explosive surrounding the powder is an effective method for producing a narrow, coherent jet of particles for the case of dense, steel particles. For lighter glass particles, more diffuse jets are formed, presumably due to shock-particle interactions and instabilities during the particle acceleration process. Hydrocode calculations of the early time particle compaction and acceleration phase illustrate the important role of shock-particle interactions within the particle bed on the particle distribution for light particles. Extending the Gurney method to a conical system is useful for illustrating the dependence of the velocity attained by the particle bed on the ratio of the particle mass to explosive mass. The Gurney velocity for a conical system is less than the corresponding value for a spherical charge, for a given ratio of particle to explosive mass, due to the lateral expansion of the products, which can be minimized by surrounding the cone with a heavy tamper.

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