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Explosively driven particle fields imaged using a high speed framing camera and particle image velocimetry

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ABSTRACT

A high speed framing camera and a particle image velocimetry instrument were used to determine the properties of explosively driven particle fields in early microsecond and later millisecond times. Test items were configured in a two inch long cylindrical shape with a half inch diameter core of organic explosive. The core was surrounded by a particle bed of aluminum or tungsten powder of a specific particle size distribution. Position data from the leading edge of the particle fronts for each charge was recorded with a high speed framing camera at early time and with a particle image velocimetry (PIV) instrument at later time to determine particle velocity. Using a PIV image, a velocity gradient along the length of the particle field was established by using the mean particle velocity value determined from three separate horizontal bands that transverse the particle field. The results showed slower particles at the beginning of the particle field closest to the source and faster ones at the end. Differences in particle dispersal, luminescence, and agglomeration were seen when changes in the initial particle size and material type were made. The aluminum powders showed extensive luminescence with agglomeration forming large particle structures while the tungsten powder showed little luminescence, agglomeration and no particle structures. Combining velocity data from the high speed framing camera and PIV, the average drag coefficient for each powder type was determined. The particle field velocities and drag coefficients at one meter showed good agreement with the numerical data produced from a computational fluid dynamics code that takes advantage of both Eulerian and Lagrangian solvers to track individual particles after a set post detonation time interval.

1. Introduction

Detonation of a heterogeneous explosive provides momentum and energy transfer from the explosive product gases and shock wave to the solid particles within or packed around the outer shell of an explosive medium. The particles become accelerated from the rapidly expanding product gases, generating a two-phase flow of material into the surrounding environment. If the explosive contains metallic particles which are reactive under high temperature and pressure and they have the correct morphology, ignition of the particles may take place if oxidizing gases are present (Frost et al., 2007). However, if inert particles are used in the explosive or ignitions of the reactive particles are delayed sufficiently until the particle number falls to a low count, the energy release will not add to the blast wave (Frost et al., 2007). Experimental studies have been conducted by Zhang et al. (2001) and Frost et al. (2007) using inert steel particles and by Frost et al. (2005, 2007) with reactive aluminum and magnesium particles. Each of these experiments used sensitized nitro methane as the driving explosive and each were compared with numerical predictions.

In addition to particle collisions, particles are thought to have significant influence on shock transmission and are affected by turbulent flows resulting in localized regions of anomalously high or low particle concentrations (Eaton and Fessler, 1994). The availability and comparison of experimental data with the output of numerical simulations yields an opportunity to improve numerical models and provide a greater understanding of particle and shock interaction in mixed media flows. Numerical shock wave investigations of this type have been reviewed by Saito et al. (2003), Zhang

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et al. (2003), Engelhardt (2008), Donahue et al. (2007), Ling et al. (2009) and Dunbar et al. (2011) for modeling specific to this research. An additional review of momentum transfer due to the interaction of shock waves with solid particles was provided by Zhang et al. (2003) where the relationships of particle shock interaction time and velocity relaxation time was described. This phenomenon occurs when the particle crosses the shock front and the ratio of the particle interaction time to the particle velocity relaxation time provides a criterion for determining whether a change in the particle velocity is significant due to the shock interaction. Accurate measurement of particle velocity is therefore critical to assess momentum and energy transfer from the gas medium to the solid particle phase. Despite the use of high speed cameras and other image based methods, Frost and Zhang (2006) stated that currently challenges remain related to the development of robust in situ diagnostics for probing the flow parameters such as particle and gas temperature, pressure, particle density, and velocity within the multiphase fireball because of the complexities of the particle field.

Ling et al. (2009) using a shock-tube problem studied the gas–particle flow arising from particle-laden driver sections. Time scales for equilibrium of the expansion fan, particles contact, and the shock wave were estimated; determining that particle laden flows behind the shock affected the speed and intensity of the shock front. Balakrishnan et al. (2010) has conducted three-dimensional simulations of inert multiphase particle systems in which he varied the particle size and volume fraction to calculate the gas and particle momentum flux and impulse loading. The method applies an approach using the Discrete Equation Method (DEM) with the use of an Eulerian–Lagrangian two phase model for dense phase particle flow, shock and gas phase interaction.

In the studies cited earlier, several methods were used to collect velocity and impulse data from the expanding particle field. These included flash X-ray and high speed video, momentum traps, blast pressure "lollipop" gauges and particle streak gauges supported with a numerical model calculation. The non-imaging techniques for the most part average small areas of the blast wave which may not have contained a homogeneous distribution of particles and therefore would not be representative of the entire flow field. Additionally, these techniques have traditionally not provided information specific to individual or small groups of 10–15 particles. Particle image velocimetry (PIV) has the ability to provide information specific to individual particles, as in particle tracking velocimetry (PTV), a subset of PIV when the flow field has low image densities. In regions of higher image density PIV can provide a resultant velocity vector for groups of well defined particle images as described by Adrian (1991). PIV is capable of providing information on particle position, size, velocity and concentration under certain conditions. Published work has demonstrated the feasibility of performing PIV measurements in the hot, high-speed exhaust plume of a solid rocket motor using natural occurring particles (Balakumar and Adrian, 2004). For short duration events PIV was demonstrated with olive oil droplets dispersed by an exploding bridge wire with their velocities determined (Murphy et al., 2005). The use of PIV for imaging explosively driven metallic particles was provided by Jenkins et al. (2010).

Small scale testing of explosively loaded items have become experimentally attractive because of the high cost associated with testing large items and the ability to provide larger numbers of test items for greater confidence in statistical evaluations. Gagliardi et al. (2005) noted that small-scale tests are initially used to obtain a useful amount of data from a small amount of explosives, considering safety, cost, and speed of production and that small-scale testing is very useful. Information on scalability of small charges, particle turbulence and dispersal are also of benefit for enhancement of numeric models.

This paper is organized as follows, in Section 2 the Methodology of test setup is described, numerical model and its assumptions, the characteristics by which the data and images will be evaluated. In Section 3 the results from the tests are presented and in Section 4 the analyses of the data is conducted. In the final section, the conclusions of the analyses are presented. The objectives of this paper are to describe the use of a high speed framing camera (HSFC) and a PIV instrument for determining particle field velocities and drag coefficients for aluminum and tungsten powders of different sizes and comparing numerical values generated using a computational fluid dynamics code (CFD) modeled for the experimental setup conditions.

2. Methodology

2.1. Experimental setup

The basic setup (Fig. 1) was the same as that reported by Jenkins et al. (2010) using the same PIV instrumentation and test support equipment with a few exceptions identified in this study. The optics box, laser and camera portal windows for this study were made from 0.5 in. sapphire material with an anti-reflective coating provided by Crystal Systems Inc. These windows were produced by the heat exchanger method (HEM) and had a 60/40 polished surface quality on the faces and a surface peak to valley (PV) flatness better than 2λ at 633 nm. The material and coating was specified to reduce the energy reflectance at 532 nm from 5% per interface determined with BK-7 glass, used in previously reported tests (Jenkins et al., 2010), to less than 0.25% per interface. Optical flatness and parallelism was improved to less than 5 arcmin due to the increased flatness of the sapphire.

Hot aluminum and tungsten particles are broad band emitters that emit 532 nm light. A filter stack was used to remove all frequencies except 532 ± 2 nm light and to reduce luminosity across the remaining spectrum from burning and hot particles; this helped prevent over saturation of the imaging chip. The reduction in light transmission was between 50% and 55% through each filter in the stack. The filter stack was varied between 2 and 3 filters depending on the expected brightness of the test event. The camera was fitted with a 105 mm Nikkor lens (Model No. 610044) made by Nikon and set at an *f*-number = 4.5. The *f*-number was reduced from previous work in order to decrease the depth of field and reduce the number of ghost images produced from the hot particles which have 532 nm light as a component in their spectrum. These images were outside of the light sheet but within the depth

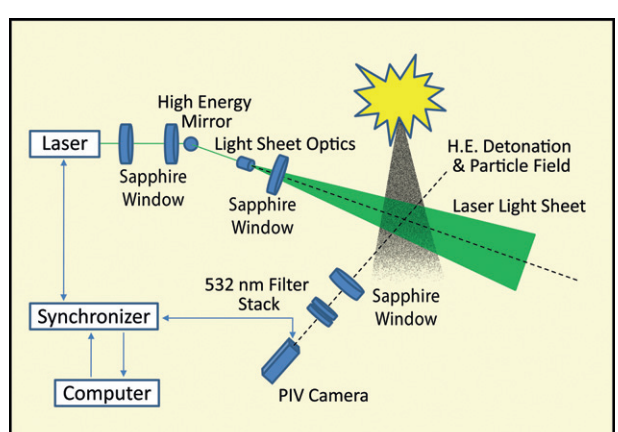

Fig. 1. PIV test setup (view top down), high explosive was set above the light sheet with particle flow in a downward direction.