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A CLASS OF EJECTA TRANSPORT TEST PROBLEMS

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Abstract. Hydro code implementations of ejecta dynamics at shocked interfaces presume a source distribution function of particulate masses and velocities, $f_0(m,u;t)$. Some properties of this source distribution function have been determined from Taylor- and supported-shockwave experiments. Such experiments measure the mass moment of f_0 under vacuum conditions assuming weak particle-particle interactions and, usually, fully inelastic scattering (capture) of ejecta particles from piezoelectric diagnostic probes. Recently, planar ejection of W particles into vacuum, Ar, and Xe gas atmospheres have been carried out to provide benchmark transport data for transport model development and validation. We present those experimental results and compare them with modeled transport of the W-ejecta particles in Ar and Xe.

Keywords: ejecta, ejecta transport, particle drag / breakup
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INTRODUCTION

The evolution of ejected material produced when a strong shockwave impinges on a free surface, or on a surface in contact with a gas, is a complex process that sensitively links to the size and velocity distributions of the ejecta, as well as to the gas viscosity, η. The size and velocity distribution of the ejected material for ductile metals depends upon the initial surface roughness, the strength and time dependence of the shockwave, and the nature of the release state that is achieved: solid, liquid, mixed phase, or damaged. Complete knowledge about these distributions is fleeting, but important to transport model development and validation.

Once a distribution of ejected material is produced, its evolution in a shocked gas contiguous to the released metal involves a complex interaction of particles, whose shape, size, and state may be changing, with each other and with the flowing gas. For the general calculation of material transport in a gas, an accurate hydrodynamic code is necessary. Assessing the validity of such a calculation requires an assessment of the accuracy of the numerical solution of the hydrodynamic algorithms and models in the code. One aspect of this assessment includes test problems with known solutions that can be compared with code calculations. To that end we present an experimental planar validation test problem for a simple transport model of spherical particles in gasses.

The model we develop includes simple drag of spherical particles with the gas at a shocked interface. Validation of simulations with the problem requires an initial particulate distribution function, which we assume separable. Because we need to know the initial particle size distribution we manufacture one with W particles of known size and average density distribution, namely, the size distribution was nominally uniform "spherical" with diameters between 0.5 and 1.0 μm.

Figure 1 shows the experimental package. The W particles were weakly bonded onto an Al substrate as a 40 μm thick, 13 mm $\times$ 13 mm square, with a nominal density of $\langle\rho_0\rangle \approx 5000$ mg/cm^3. During the experiment a shock was driven through the target via a 16 mm tall, 25 mm diameter calcitol [1] high ex-

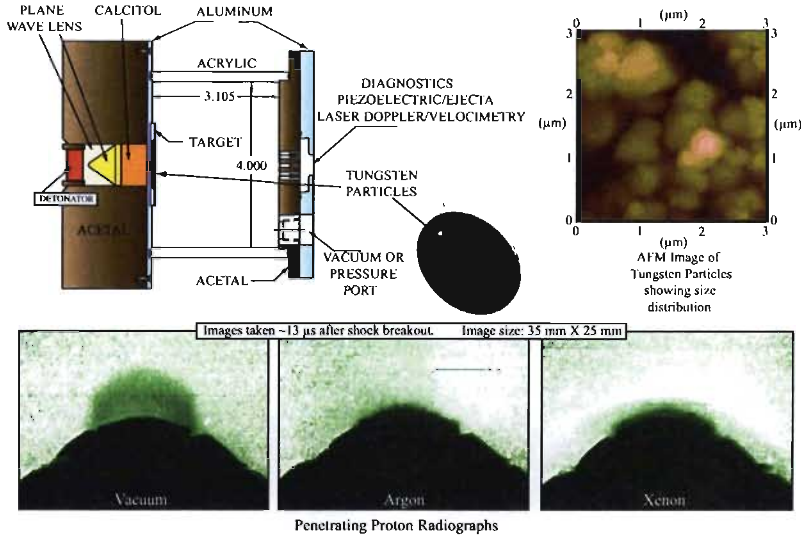

FIGURE 1. The experimental package design, together with an atomic force microscope image of the W-particle layer, and three late time proton radiographs, one each for vacuum, Ar, and Xe; the ejecta distributions are clearly quite different.

plosive cylinder. Pressurization of the package with Ar or Xe was accomplished using a clear acrylic can through which multiple proton-radiographs were taken during the experiment to image the evolution of the target and ejecta cloud. In addition, time-dependent $LiNbO_3$ piezoelectric (piezo) probes measured the pressure due to accumulation of ejecta on the probe from which the time-dependent ejecta mass distribution can be determined [2, 3]. Lastly, laser Doppler velocimetry (LDV) was used to diagnose the jump velocity and estimate the shockwave loading pressures. [4]

The experiments were executed at the Los Alamos National Laboratory Proton Radiography Facility in three geometries. One was a vacuum baseline experiment to give the vacuum ejecta mass distribution, one was pressurized with Ar to $\approx$ 9.65 bar, and one with Xe to $\approx$ 2.9 bar, all at an initial temperature of 300 K. These pressures gave nominal gas densities of $\rho_g \approx 17$ mg/cm^3.

The LDV on the three experiments showed a (Al) free-surface jump velocity of $u_{fs} \approx 1.25$ mm/μs. We assume the W particles are ejected instantaneously at time $t_0 = 0$ when the shockwave releases at the vacuum/gas-metal interface; we further assume that the ejecta velocity is simply determined by the ejecta time of arrival t, relative to t_0, over the distance $z = 38.2$ mm from the W surface to the piezo probe, a time and distance that gives the nominal ejecta velocity $u(t) \equiv z/t$. Under the assumption of inelastic scattering, the pressure at the piezo probe surface is $\rho_{ej}u^2(t)$.

Using the measured time-dependent piezo probe pressure and the resulting vacuum ejecta mass distribution, the hydrodynamic equations developed are used to calculate ejecta mass distributions and expected time-dependent piezo probe pressure for ejecta transported through Ar and Xe. The results of these calculations are then compared to the measured piezo probe pressure profiles for the Ar and Xe experiments.

DISTRIBUTION FUNCTIONS

The distribution function of particles with position z, velocity $u(t)$ and mass m, in the volume element $dz\,du\,dm$ about z, $u(t)$ and m at time t, is denoted by $f(z,u,m;t)$. The number of particles in this volume element is given by: $f(z,u,m;t)dz\,du\,dm$. Ignoring particle-particle interactions we have

$$f(z,u,m;t) = \int dz_0 du_0\, \delta(z - z(t))\delta(u - u(t)) f_0(z_0,u_0,m;t_0), \tag{1}$$

where $f_0(z_0,u_0,m)$ is the initial distribution function at $t=0$. The particle positions and velocities $z(t)$ and $u(t)$ depend implicitly on z_0, u_0 and m via the initial values for the solutions of the equations of motion: $\dot{u}(t)=\ddot{z}(t)=F(t)/m$ in our 1D geometry.

The connection between the distribution function f and the measured piezo-probe pin pressure $P(t)$ is:

$$P(t)=\int dmdu\big(mu^2 f(z,u,m;t)\big), \qquad (2)$$

giving for vacuum ejection

$$P_0(t;z)=\frac{u^2(t)}{tA}\int dm\left(mf_0(z_0,u(t),m)\right), \quad (3)$$

where A is the active area of the peizo-probe, implying that

$$\rho_0(t;z)=\int dmdz_0\frac{f_0(z_0,u(t),m)}{tA}=\frac{P_0(t)}{u(t)^2}, \quad (4)$$

where $P(t)$ and $u(t)$ are the pressure and velocity at z, and t is relative to the shockwave breakout at the free surface.

Non-zero external field: particle drag

For nonzero external fields, Eq. 1 remains valid, but the particulate equations of motion are more complicated. We consider the case of particle drag:

$$F=-\frac{1}{2}\rho_g C_D A|u-u_g|(u-u_g) \qquad (5)$$

where C_D is the drag coefficient, A is the area in the direction of the propagation velocity, and the subscript g denotes gas quantities. We consider expressions for the low Reynolds number Re dependence for spherical shape dependent drag coefficients:

$$Re\le 10^3:\ C_D=\frac{24}{Re}(1+0.167Re^{2/3}) \qquad (6)$$

where $Re=D_p|u_p-u_g|/\nu$, and ν is the kinematic viscosity defined in terms of the coefficient of viscosity as $\eta=\rho_g\nu$, and D_p and u_p are the particle diameter and velocity.

Writing the solution for $z(t)$ as:

$$z(t,u_0)=u_{fs}t+u_0\tau(t,u_0) \qquad (7)$$

$F(t)/m$ may be solved for $\tau(t,u_0)$ with the result:

$$\tau(t,u_0)=3t_0B^{-\frac{3}{2}}\left\{\sqrt{B}\left[1-\frac{1}{\sqrt{1+B(1-x^2)}}\right]\right. \qquad (8)$$
$$\left.-\left[\sin^{-1}\sqrt{\frac{B}{1+B}}-\sin^{-1}\left(x\sqrt{\frac{B}{1+B}}\right)\right]\right\}$$
$$B=0.167(Re^{(0)})^{\frac{2}{3}},\ x=e^{-\frac{t}{3t_0}},\ t_0=\frac{1}{18}\frac{\rho_p D_p^2}{\eta},$$

where

$$Re^{(0)}=\frac{D_p|u_p(t=0)-u_g|}{\nu},\quad m_p=\frac{\pi}{6}\rho_p D_p^3, \quad (9)$$

and m_p and ρ_p are the particle mass and density. These trajectories are to be substituted in the right hand side of Eq. 1.

When the distribution function f_0 is separable, i.e.

$$f_0(u,m)=f_0^{(1)}(u)f_0^{(2)}(m), \qquad (10)$$

simplifications can be made and the expressions for ρ and P may be written as one dimensional integrals. For the spherical case we are considering here, the solution to $u_0(z,t)$ must be obtained numerically except in the case of Stokes drag, i.e. low Re flow when it can be obtained analytically.

W EJECTA TRANSPORT IN AR AND XE

The recent Taylor wave experiments can be analyzed in terms of the above expressions. Although the size distribution of the W particles has a small dispersion about 1 μm, for a preliminary analysis we have taken the mass distribution function $f_0^{(2)}(m)$ above to be a δ-function. In this case the integral for $P(t)$ becomes a simple function of t at the position z of the probe from the free surface given by

$$P(z,t)=P_0\left(\frac{t}{\lambda(z,t)}\right) \qquad (11)$$
$$\times\ \frac{t}{\lambda(z,t)\tau(t)}\left[1-\frac{t}{t_0}\frac{1}{\lambda(z,t)}\left(1-\frac{u_{fs}t}{z}\right)\right]^2,$$

where

$$\lambda(z,t)=1+\left(\frac{t}{\tau(t)}-1\right)\left(1-\frac{u_{fs}t}{z}\right), \qquad (12)$$
$$\tau(t)=t_0\left(1-e^{-\frac{t}{t_0}}\right). \qquad (13)$$

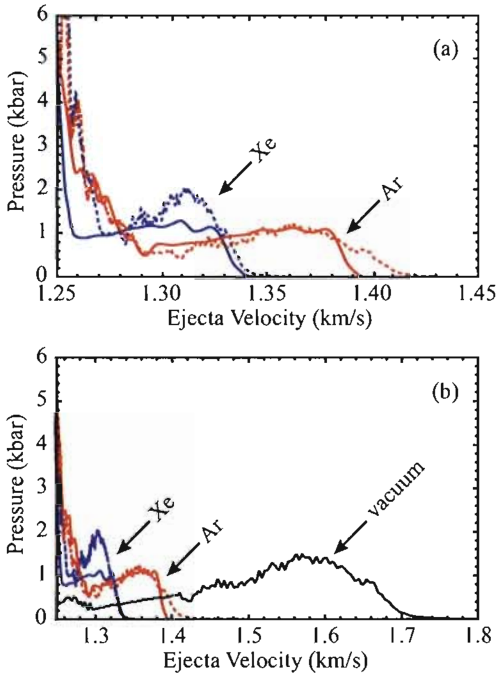

FIGURE 2. (a) Ar (red) and Xe (blue) data (solid) and calculations (dashed) assuming a distribution of particle diameters in the ratios $0.125[0.2\ \mu\text{m}] + 0.125[0.3\ \mu\text{m}] + 0.125[0.4\ \mu\text{m}] + 0.125[0.5\ \mu\text{m}] + 0.5[1\ \mu\text{m}]$. (b) Results including vacuum data (black) upon which the analysis is based. (Color online.)

Figure 2(a) shows a comparison with Ar experimental data for values of $\eta = 100\ \mu$Pa-s and $t_0 = 9.0\ \mu$s and a distribution in particle sizes from 0.2 to 1.0 μm. With the same source particle distribution, the calculated $P(t)$ for Xe would only depend on the Xe viscosity. Figure 2(a) also shows the comparison for the Xe gas data assuming a viscosity of $\eta = 186\ \mu$Pa-s to fit the leading edge of the distribution.

It is evident that the Xe calculation over-predicts the pin data at low velocities implying that the W particles are evolving faster than expected. An indication of why this might be so can be found in the Hugoniot state achieved behind the gas shock front. Gas shock temperatures estimated from hydro simulations using tabular EOS's give 2800 K and 7800 K for Ar and Xe, respectively. Since the low pressure melting temperature of W is approximately 3700 K it is likely that the low velocity discrepancy is due to the fast breakup of molten W droplets which would shift the low velocity pressure (mass distribution) to lower velocities. Figure 2(b) summarizes the analysis for gas transport pin data in Ar and Xe and includes the vacuum data upon which the analysis is based.

DISCUSSION

We presented a set of solutions for the transport of particles ejected into a gas from a shocked interface under the assumption that the distribution function is separable. Solutions were presented for the case of particulate drag for spherical shapes, and expressions were derived for the particle density as a function of spatial coordinate and time, and for the piezoelectric probe response at position z as a function of time. These expressions may be used to verify computer code implementations of ejecta transport given an initial source distribution. We used these expressions in the analysis of ejecta transport validation measurements, for W particles into Ar and Xe gases. The analysis of these experiments is preliminary, in particular the microscopic analysis of the initial W layer is in progress. The preliminary indications of particulate break-up in the Xe experiments suggest that experiments that span the gas temperature region below and above the W melting temperature are of interest. The solutions presented include particle drag only. There are other terms on the right hand side of Eq. 5 that may modify the transport results. It should also be noted that the thermal transport between particle and gas has not been considered in the equations presented here nor have Mach number effects been included. Nevertheless the agreement between experiment and theory in a minimal model is encouraging.

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