Numerical Investigation of Laser-Driven Shock Interaction with a Deformable Particle

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To accurately simulate material behavior at relatively low temperatures, i.e., in the sub-eV range, we require models with strength properties in the solid/liquid regime. Such models are not often included in most radiation-hydrodynamics simulation codes including *FLASH*,[1] which are used as tools to design high-energy-density (HED) experiments. In addition, high-temperature equation-of-state (EOS) models used for simulations become less predictive of the thermodynamic material properties necessary for describing the hydrodynamic processes taking place at low temperatures. For instance, in *FLASH*, only thermal pressure contributes to the computation of the local sound speed. This entirely neglects the existence of nonthermal pressure, which is a property that determines the behavior of shock-compressed solids. Theoretically, this leads to higher material compressibility even at low shock pressures. Veification was carried out in 2-D *FLASH* simulations of an ~50-GPa ablation-driven shock propagating over an Al particle embedded in epoxy (CH) and observed ~3.5× compression and significant deformation of the particle in Fig. 1(a). The predicted evolution of the particle modeled with *IONMIX* EOS did not reproduce the experimental shock Hugoniot.[2] Hence, a technique was developed to implement a modified form of ideal gas EOS to model the materials (including Al, Ti, and W) and study the dynamics of the embedded particle. The simulated shock Hugoniots of multiple materials modeled using this technique compared well with experimental data. Examination of the flow field [see Fig. 1(b)] demonstrated that the unsteady drag coefficient for the particle featured a peak drag due to an unsteady interaction with the transmitted shock and a drag minimum due to shock focusing on the rear end of the particle. However, unlike previous studies performed without laser drives, the particle drag coefficient featured a second minimum due to rarefaction stretching associated with laser shutoff.

Numerous simulations were conducted that investigated the particle response for a range of particle densities, sizes, and acoustic impedances. These results revealed that lighter particles, such as Al, gained significant momentum up to 96% from the shocked CH compared to 29% in the case of heavier W. Finally, the effect of particle acoustic impedance on the bulk particle response was studied. Despite differences observed in the early stage of shock interaction, the acoustic impedance did not influence the peak particle velocity. This identified particle-to-host density ratio as a dominant factor in determining the inviscid terminal velocity of the particle. Time-scale analysis in previous works has pointed out that the shock–particle interaction time scale could be of the same order as the viscous time scale, particularly for condensed-matter systems.[3] Therefore, viscous effects coupled with rarefaction stretching effect could be important for particle drag calculation in the intermediate to later stages of shock interaction.

Finally, the simplified approach of modeling materials for hydrodynamic simulations presented in this work could be useful in studying propagation of shock waves through condensed media, in particular, dispersal of particles in multiphase explosives. The method could also be applied to understand the particle dynamics of tracers for their potential applications to x-ray particle image velocimetry in HED flows.

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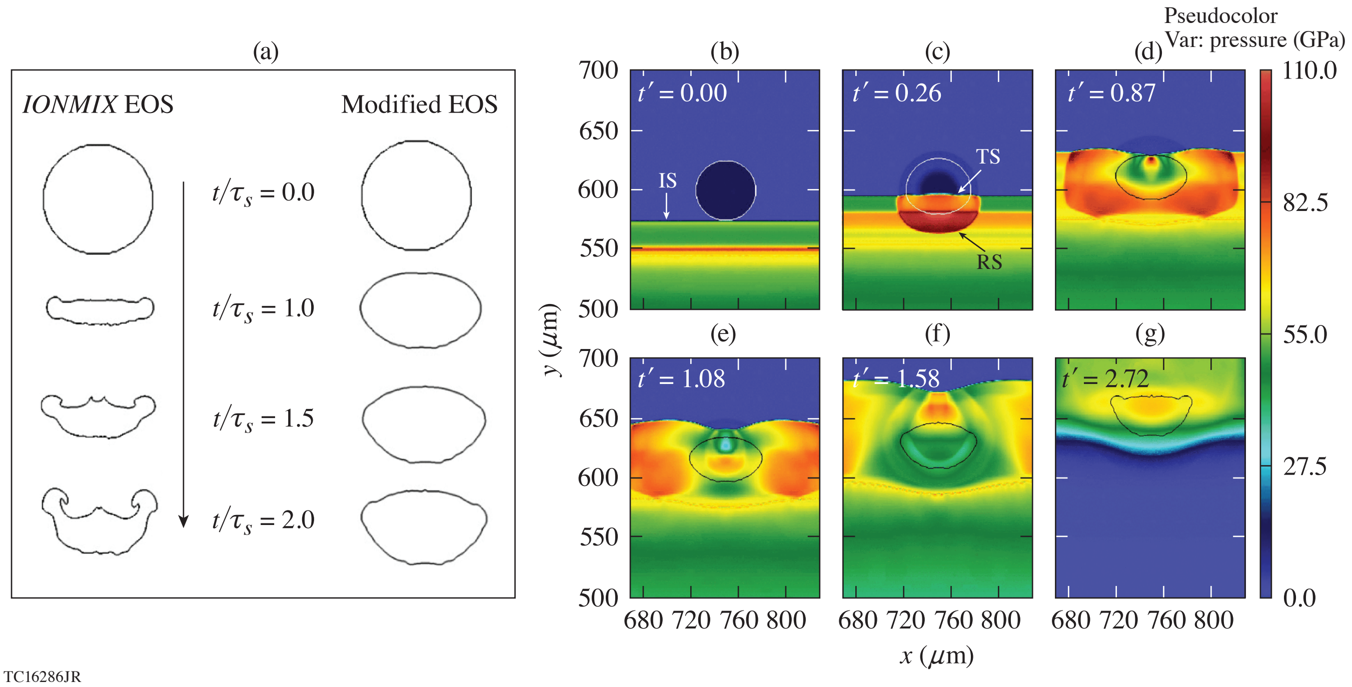

Figure 1
(a) Deformation of an Al particle in CH subjected to a 55-GPa shock with materials modeled using *IONMIX* EOS and a modified ideal gas EOS. τ_s is the shock–particle interaction time based on the particle diameter d_p and shock speed u_s. (b) Contour plots of pressure at increasing times for the post-shock pressure of 55 GPa in CH. Computational domain near the Al particle (modeled using modified EOS) is shown. The white curve [in (b) and (c)] or black curve [in (d)–(g)] is a particle interface constructed using cells around the particle with 25% mass-fraction cutoff. IS, TS, and RS denote incident, transmitted and reflected shock, respectively.

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