Radiation-coupled front-tracking simulations for laser-driven shock experiments

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Abstract

The purpose of this paper is to develop a numerical algorithm to track the preheat interface motion driven by radiation transfer in high-intensity laser experiments. Our front-tracking algorithm is coupled to a radiation process through an inter-package coupling by connecting the output from a radhydro code HYADES to the input of FronTier code of front tracking. Our coupled algorithm is validated by comparing simulation results from both codes in both low and high radiation cases. Significant interface motion and deformation of the harmonic perturbation due to radiation preheat are observed in high radiation heat case.

Keywords: Front tracking; Radiation coupling; Preheat motion

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1. Introduction

The aim of laser astrophysics experiments is to probe astrophysical dynamics directly by creating scaled reproductions of the astrophysical systems in the laboratory. The first spherically diverging, hydrodynamically unstable laboratory experiments of relevance to supernovae (SNe) were reported in [1]. The experiments use laser radiation to explode a hemispherical capsule, having a perturbed outer surface, which is embedded within a volume of low-density foam. These experiments and simulations provide a well-scaled test of computer models of supernova explosion hydrodynamics. Here we address the impact of the radiation preheat on the structure at the interface by the time the shock reaches it. One-dimensional calculations find a level of radiation preheat that causes the interface to move about $2–50 \mu m$ by the time the shock reaches it, depending upon the target properties.

The purpose of this paper is to develop a radiation coupled front-tracking algorithm to track the preheat motion of the interface. Front tracking as implemented in the code FronTier includes the ability to handle multidimensional wave interactions in both two [7,9,10] and three [6,5] space dimensions and is based on a composite algorithm that combines shock capturing on a spatial grid with a specialized treatment of the flow near the tracked fronts. Here, we develop a radiation front-tracking coupling algorithm to connect radiation output from HYADES [11] to FronTier input. The algorithm is designed to handle the following two cases. If radiation output data are taken when radiation effect is negligible, the data will be interpolated onto a front-tracking grid as the initial data for the simulation. On the other hand, if the radiation process is important, the radiation code will provide the heat rate data in addition to the state data. The front-tracking code will incorporate the radiation heat data into its energy equation as a source term. We have simulated two preheat laser experiments in low and high radiation heating. For the high radiation case, we have conducted simulations of both one- and two-dimensional preheat motions. We have observed significant interface motion leading to a reduction of the interface perturbation amplitude before the shock reaches the interface. Validation has been carried out by comparing the outputs of FronTier and HYADES.

2. Radiation-coupled front-tracking algorithm

Front tracking is a numerical method in which selected waves are explicitly represented in a discrete form of the solution. If the system of equations consists of a set of hyperbolic conservation laws, $u_t + \nabla \cdot f = h$, then the instantaneous velocity $s$ of a discontinuity surface satisfies the Rankine–Hugoniot equations, $s[f] = [f] \cdot n$. Here $n$ is the unit normal to the discontinuity surface. During a time step propagation, the type of a wave, and the flow field in a neighborhood of the wave determine a local time-integrated velocity for each point on the wave in the direction normal to the wave front. Wave propagation consists of moving each point a distance $s \Delta t$ in the normal direction as well as computing the time updated states at the new position. Tracking preserves the mathematical structure of the discontinuous waves by maintaining the discrete jump at the wave front, thus eliminating numerical diffusion across the front. It also allows for the direct inclusion of the appropriate
flow equations for the wave front in the numerical solution. For a detailed description of
the front tracking algorithm, we refer to Glimm, Grove and Zhang [8]. The validation in
spherical geometry was carried out by comparison with experiment, see Drake et al. [1]
where supernova experiments and simulations were reported. For other validation studies
in planar geometry, we refer to [4].

Front tracking is a fast algorithm in the sense that it can reduce the level of mesh re-
finement, needed to achieve a specified error tolerance by a significant factor compared to
Corresponding methods without tracking. A comparison study was carried out for an unper-
turbed spherical shock interface interaction. The density plots for the spherical simulations
with and without tracking are shown in Fig. 1, where we see the untracked interface was
highly smeared by numerical diffusion. The main results in [2,3] can be summarized as
follows. Tracking the contact can effectively reduce both the contact error and the total
error by a significant factor. The mesh size needed to achieve a fixed error tolerance can
be reduced by as much as a factor of eight per spatial dimension. A factor of $8^4 = 4096$
fewer space–time zones for a three space dimensional computation are then required for
comparable accuracy.

The simulations in this paper are based on the Euler equations:

$$\rho_t + \nabla \cdot (\rho \mathbf{v}) + \frac{\rho \mathbf{v} \cdot \mathbf{v}}{r} = 0,$$

$$\rho \mathbf{v}_t + \nabla \cdot (\rho \mathbf{v} \otimes \mathbf{v}) + \nabla P + \frac{\rho \mathbf{v} \cdot \mathbf{v}}{r} = 0,$$

$$\rho (E)_t + \nabla \cdot \rho \mathbf{v}(E + P/\rho) + \frac{\rho \mathbf{v} \cdot \mathbf{v} (E + P/\rho)}{r} = Q$$

where $\rho$ is the mass density, $\mathbf{v}$ the fluid velocity, $P$ the thermodynamic pressure, $E = e + \frac{1}{2} \mathbf{v} \cdot \mathbf{v}$
the specific total energy, and $e$ the specific internal energy. The variables $\rho$, $P$, and $e$ are
related by a thermodynamic equation of state $P = P(\rho, e)$. For simplicity we assume a
perfect gas equation of state $P = (\gamma - 1)pe$, with $\gamma > 1$. The simulations reported in this
paper use the value $\gamma = \frac{5}{3}$. The geometrical parameter $x$ has the value zero for rectangular
geometries. For axisymmetric flow $a = 1$, while $a = 2$ for one-dimensional (1D) spherical symmetry. For spherical symmetry $u$ is the radial component of velocity and $r$ is the distance from a point to the origin. For axisymmetry $u$ is the radial component of the projection of the fluid velocity into the $x − y$ plane and $r$ is the distance of a point from the $z$ axis. Here $Q$ is the radiation heat rate per unit volume.

For coupling the radiation process to FronTier code, we use a pipeline method: a connection of the output of one code to the input of another. This method requires matching and interpolating data across dissimilar grids. The research team at University of Michigan prepared initial conditions from a 1D radiation-hydrodynamic (radhydro) code HYADES which is applied in 1D slices and used in our front tracking simulation. The algorithm for including a radiation heat source in FronTier was developed. The idea is that the output data from the radhydro code taken as front-tracking input before the interface starts to move due to radiation preheat. However, the radiation heat rate data are needed from this time until the time when the radiation effect diminishes. We use this information to set up a time- and space-dependent energy source $Q$ for the front tracking.

### 3. Low radiation heat

The target has a 75 µm thick layer of polymide (at $\rho = 1.41$ g/cm³), followed by a 75 µm thick layer of brominated plastic (4.3% atomic Br, $\rho = 1.42$ g/cm³), followed in turn by a low-density ($\rho = 0.1$ g/cm³) carbon foam, in a planar geometry. These experiments and simulations are intended to be a scaled representation of a small segment of an exploding star [12]. A strong shock is generated by Omega laser incident on the plastic. The HYADES [11] code is used for radiation transfer in the laser deposition experiments and to set up initial conditions and the radiation heat rate for FronTier input. HYADES as used here is a one-dimensional, Lagrangian, radhydro code with multigroup diffusion radiation transport based on average-atom opacities, tabular equation of state using SESAME tables, and flux-limited diffusive electron heat transport. HYADES is believed to accurately calculate the radiation preheat produced by the interaction of the laser beam and the hot plasma it produces.

The output of HYADES at 1 ns was shown in Fig. 2 together with the space-time heat rate up to 2 ns, which will be used as energy source for FronTier. The contact interface is located at 150 µm. We ran the FronTier simulation with the input data displayed in Fig. 2 from 1 to 2 ns. The profiles for density, pressure, and velocity are shown for 1, 1.5, and 2 ns for both FronTier and HYADES results in Fig. 3, which demonstrates an excellent agreement between two codes.

### 4. High radiation heat

In this case, a different target that would produce much higher levels of radiation preheat was used. The entire layer of dense material is now brominated plastic (150µm thick, $\rho = 1.42$ g/cm³). The interaction of the laser with this material produces much higher levels of radiation preheat. In addition, these conditions may model preheat by energetic
Fig. 2. The images in the first row are the HY ADES output at 1 ns as initial condition for FronTier for the low radiation case. The second row is the space- and time-dependent radiation heat rate from HY ADES as energy source for FronTier.

electrons. HY ADES output at time 1 ns are shown in Fig. 4 from which we see that heat rate has spread over more space and is higher in magnitude than in the case stated in the previous section. The FronTier simulation is conducted from time 1–2.4 ns with the input from Fig. 4. Fig. 5 shows the comparison for density, pressure, and velocity for times 1, 1.6, and 2.4 ns for both codes. Again the agreement between FronTier and HY ADES is obtained; we find the interface has moved by 25 μm at 2.4 ns when the shock is yet to reach the interface. Such preheat motion is not significant in the low radiation heat case. From the density and velocity plots we also see that the material ahead of interface has been perturbed at time 2.4 ns and has positive velocity.

Our 2D FronTier simulation is carried out for a 1200 μm long axisymmetric tube with a radius of 400 μm in the \((r, z)\) domain in cylindrical geometry. The initial contact interface is perturbed by 8 sine waves with peak-valley amplitude of 5 μm at the height of 150 μm. In order to set up the initial data for the 2D run, we perturb the 1D data of Fig. 4 in six equal \(r\)-spaced vertical \(z\) directions with interface positions shifted along sine wave. Then
these data are mirror reflected to generate the data on the full sine wave, which in turn are replicated to the interface of eight sine waves and the whole domain so that states at any point can be obtained by interpolation. The initial perturbation had a peak-valley amplitude of 5 μm. The interface evolution for our front tracking simulation is shown in Fig. 6 for time 1, 1.6, 2.4, 6, and 10 ns. Fig. 6 again demonstrates that the interface has moved by an amount similar to the corresponding 1D simulation when the shock is about to reach interface at 2.4 ns. But what is more interesting is that the shape of perturbation is changed before the shock reaches the interface. We see the interface is flattened at 2.4 ns. In addition, by this time velocity perturbations exist along the interface, so that the initial conditions seen by the shock include perturbations in both density and velocity. The amplitude and growth rate of the perturbation are plotted as functions of time in Fig. 7, where we observe that amplitude increases slightly from 5 to 5.6 μm between 1 to 1.6 ns, then decreases significantly from 1.7 to 2.5 ns when the shock has almost hit the interface. Mushroom-type interface shapes which are characteristics of Richtmyer–Meshkov instability are demonstrated at later times 6 and 10 ns in Fig. 6.
5. Conclusions

We have presented a radiation coupled front-tracking algorithm for intensive laser experiments in laboratory astrophysical system. Here we have proposed a pipeline method for inter-package coupling where the radhydro output is piped to the hydrodynamic input. The radiation heat rate from HYADES for the period of radiation transfer is converted to an energy source in space-time zones for FronTier, where interpolation is used to map the data in a Lagrangian moving mesh to the data in Eulerian fixed grid.

Our simulations are carried out for both low and high radiation heat rates in one- and two-dimensional cases. Our results are validated by comparing the FronTier output to the data produced by HYADES in the one-dimensional case. We have observed significant preheat interface motion due to radiation process. We also find the shape of the interface perturbation can be altered enormously by the radiation preheat. This motivates direct experimental
Fig. 5. Comparison of FronTier and HYADES at 1, 1.6, and 2.4 ns for the high radiation case. The pictures show profiles for density, pressure and velocity.

Fig. 6. Density plots for a cylindrical simulation at 1, 1.6, 2.4, 6, and 10 ns. The interface is initially perturbed by eight sine waves with peak-valley amplitude of 5 μm and driven by an upward shock. The left boundary is the rotational axis.
measurements of preheat as part of any complete study of shock-driven instabilities by such experimental methods.

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