2D LARED-H Simulation of Ignition Hohlraum

ZHAI Chuan-lei, PEI Wen-bing， ZENG Qing-hong

***Abstract*—The integrated simulation of multi-material ignition hohlraum, consist of a cylindrical hohlraum and an imploding capsule, is realized in two dimensions using the LARED-H non-LTE radiation hydrodynamics code. The key problem in the integrated simulation is the multi-material large deformation problem. Arbitrary Lagrangian-Eulerian method is used to treat the large deformation problem and multi-material cells are introduced when the material interface is severely distorted. Satisfactory numerical results are acquired in the integrated simulation of ignition hohlraum, which show the performance of LARED-H code.**

***Index Terms*—Multi-material large deformation problem, Multi-material cell, Radiation hydrodynamics, Inertial confinement fusion**

I. Introduction

In the indirect laser-driven inertial confinement fusion [1] (ICF), the laser beams are firstly injected into a high-*Z* enclosure, called hohlraum. The high-Z material inside the hohlraum absorbs most of the laser energy and convert to x-rays which ablate the capsule laid at the hohlraum center and drive implosion.

Physics of indirect laser-driven ICF involves very complicated physical processes, which can be separated into the hohlraum physics and capsule physics [2]. The hohlraum physics includes laser propagation and absorption, non-local electron heat conduction, hohlraum plasma dynamics, non-LTE atomic physics, *x*-ray conversion and radiation transport. The capsule physics includes radiation ablation, drive symmetry and hydrodynamic instability, and ignition physics. These processes with different characteristic spatial scales and temporal scales are coupled with each other. The indirect laser-driven ICF is therefore a complicated multi-material, multi-physics and high non-LTE issue. These materials are severely distorted in the whole process, which is the key problem in the integrated simulation of hohlraum.

Many codes are developed to study the physical processes and design targets for inertial confinement fusion in USA. LASNEX [3] and HYDRA [4] are the famous two. LASNEX is a two dimensional axisymmetric radiation hydrodynamics codes, which played an important role in the study of ICF and target design on the NOVA and NIF for about thirty years. HYDRA is a three dimensional radiation hydrodynamics code based upon a block structured mesh, which is mostly used to study the implosion of capsule. Both LASNEX and HYDRA have Arbitrary Lagrangian-Eulerian [5] (ALE) capability to deal with multi-material large deformation problem.

In the last decade, a system of numerical simulation for ICF research has been set up in our institute, which is named LARED code family. LARED code family contains six different 2D (and partially 3D) code, each code can separately study the key physics issues. We refer the readers to [2] for details of LARED code family. As one member of LARED code family, LARED-H code is mainly used to study the laser target coupling and hohlraum physics. The LARED-H code gives the radiation field inside the hohlraum, which is used as radiation source by other codes to study the capsule implosion process or other applications.

Now we try to use LARED-H code to accomplish the integrated simulation of hohlraum and capsule. In the integrated simulation of ignition hohlraum, the plasmas ablated from hohlraum wall and capsule collides in the hohlraum, which cause the large deformation problem of lagrangian meshes. Since the temperature is high and the density is low, the ablated plasmas is nearly transparent and doesn't affect the radiation field inside the hohlraum and energy assignment between the hohlraum wall and capsule.

To overcome the large deformation problem, arbitrary Lagrangian-Eulerian method is adopted in LARED-H code. The number and location of meshes are reconstructed when the lagrangian mesh is severely distorted, and then the lagrangian simulation continues on the new meshes circularly. When the material interface is too distorted to be maintained as grid line in the high temperature and low density region, just like eulerian method, the multi-material cells are introduced in order to reconstruct high quality mesh.

The numerical method of multi-material cells in lagrangian radiation hydrodynamics is still a problem. For hydrodynamics problem, Shashkov [6, 7] provide some closure models based on pressure relaxation method recently. But the relative article for radiation hydrodynamics has not been seen yet. In this article, we provide a simple method for multi-material cells in lagrangian radiation hydrodynamics and represent some numerical results to demonstrate the good performance of our code.

The remainder of this article is organized as follows. In Section 2, we introduce the LARED-H code briefly. Then, the numerical algorithm of multi-material cells for radiation hydrodynamics problem in lagrangian step is given in section 3. In Section 4, some simulation results are given to verify the

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current capacity of the LARED-H code. Finally some conclusions are given in Section 5.

II. LARED-H CODE

LARED-H is a two-dimensional multi-physics radiation hydrodynamics code. The LARED-H code is based on multi block grid. Each block is partitioned to logically rectangular meshes. Blocks are connected in harmony, which means the boundary nodes between two blocks must be same. Blocks can joint with singularity points of reduced or enhanced connectivity, which has less or more than four blocks all around.

LARED-H includes several packages, with each package calculates one physical process separately.

Firstly, hydrodynamics package is included which calculates the movement of plasmas. Typically, the hydrodynamics is Lagrangian in which the meshes move along with the material. LARED-H code use a staggered grid, which means the velocities are defined at nodes while the density, pressure, and other variables are defined in the cell. The moment equations are discretized with IGA scheme [8], which can preserve the sphere symmetry for one dimensional problem. Artificial viscosity is adopted to treat shock waves. Velocity filter is used to damp spurious mesh oscillations.

Secondly, three-temperature approximation is adopted in our code, which assumes the electrons, ions and radiation field are in local thermodynamic equilibrium (LTE) respectively, each having its own temperature. three-temperature coupling diffusion equations are discritized in implicit method. Picard linearization is used to treat the nonlinear heat conducting coefficients, and the linearized diffusion equations are discretized with diffusion scheme given in [9]. The resulting linearized system is then solved by iterative matrix methods.

Thirdly, a NLTE atomic physics package is included which calculates the equations of bound electron population and the energy exchange term between electrons and radiation field for the high-Z material in the hohlraum wall with average-atom model. Four pair atomic physics process, such as photo-ionization and radiative recombination, electron collision ionization and recombination, electron collision excitation and deexcitation, line absorption and emission, are considered in our code.

Fourthly, a laser ray trace and deposit package is also included which calculates laser propagation and energy absorption in the plasma. Laser propagation and deposition is handled in the geometric optics approximations. The laser beam is broken up into several hundred rays which travel through the code's spatial mesh, bend according to the laws of refraction and lose energy to absorption by inverse bremsstrahlung and the resonant excitation of plasma waves.

Finally, when the LARED-H code leads to severe mesh distortions, a rezone package is applied. The number of blocks and meshes may be changed. When the material interface is too severely distort to be maintained as grid line, multi-material cells are introduced so that the meshes have good geometric quality. The mass and inner energy of each material are remapped from old meshes to new meshes conservatively. The velocities are interpolated from old nodes to new nodes.

III. NUMERICAL ALGORITHM OF MULTI-MATERIAL CELLS

In lagrangian calculation, the masses of each material in multi-material cells are not changed, so the mass fractions of each material don't vary. We assume that the volume fractions of each material in multi-material cell don't vary in time. In the multi-material, pressure is defined as the volume fraction averaged pressure of each material according to the Dalton law of partial pressure.

In the multi-material cell, we assume that the electron, ion and radiation temperatures of each material are the same, so we can solve three-temperature in whole computational region. The three-temperature equations are

$$C_{ve}\frac{dT_e}{dt}+T_e\left(\frac{\partial p_e}{\partial T_e}\right)_\rho\frac{d}{dt}\left(\frac{1}{\rho}\right)=-\frac{1}{\rho}\nabla\cdot\left(\kappa_e\nabla T_e\right)+W_L-W_{ei}-W_{er},$$

$$C_{vi}\frac{dT_i}{dt}+T_i\left(\frac{\partial p_i}{\partial T_i}\right)_\rho\frac{d}{dt}\left(\frac{1}{\rho}\right)=-\frac{1}{\rho}\nabla\cdot\left(\kappa_i\nabla T_i\right)+W_{ei},$$

$$C_{vr}\frac{dT_r}{dt}+T_r\left(\frac{\partial p_r}{\partial T_r}\right)_\rho\frac{d}{dt}\left(\frac{1}{\rho}\right)=-\frac{1}{\rho}\nabla\cdot\left(\kappa_r\nabla T_r\right)+W_{er}.$$

In these equations, ρ is the average mass density in the cell; (p_e,T_e,C_{ve}), (p_i,T_i,C_{vi}) and (p_r,T_r,C_{vr}) is the pressures, temperatures and specific heats for the electron, ion and radiation respectively; κ_e, κ_i and κ_r are heat conducting coefficients for electron, ion and radiation respectively; W_L is the deposition term of laser energy; W_{ei} and W_{er} are energy exchange terms between electron and ion, electron and radiation respectively. In the multi-material cells, the heat conducting coefficients are defined as the volume fraction weighted harmonic average, and others coefficients are defines as the mass fraction weighted average. We express in formula as follows:

$$\frac{1}{\kappa_{e,i,r}}=\frac{1}{\frac{vof^1}{\kappa^1_{e,i,r}}+\frac{vof^2}{\kappa^2_{e,i,r}}}$$

$$C_{ve,i,r}=mof^1C^1_{ve,i,r}+mof^2C^2_{ve,i,r}$$

$$W_{ei,er}=mof^1C^1_{ei,er}+mof^2C^2_{ei,er}$$

where the superscript denotes the coefficients for each material and the variables mof and vof are the mass fraction and volume fraction for each material respectively.

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IV. Numerical results

A. numerical results of method in multi-material cells

The numerical algorithm of multi-material cells is validated in this section. Firstly, we test hydrodynamics problem. We compare numerical results of the two-material Sod problem. The government equations are inviscid Euler equations. The computational domain is [0, 1], and the initial discontinuity is at 0.5. Material on left and right side are both ideal gases, and the initial states on left and right side are $\gamma = 2, \rho = 1.0, u = 0, p = 2.5$ and $\gamma = 1.4, \rho = 0.125, u = 0, p = 0.1$ respectively.

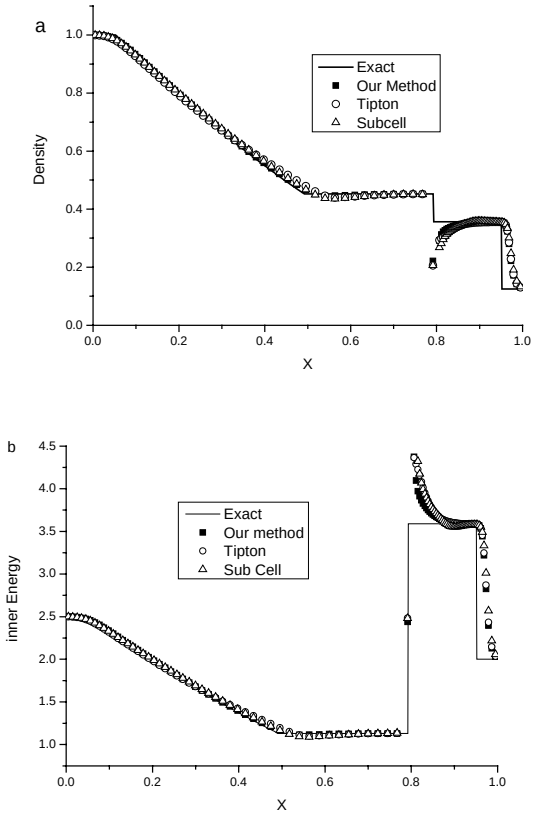

Fig. 1 Simulation results of two material Sod problem at t=0.2 Density(a), Specific internal energy(b).

Table 1. Comparison of Material interface at t=0.2.

method type	location of interface	left node of fiftieth cell	right node of fiftieth cell
Our method	0.7906542	0.7778398	0.8034685
Tipton	0.8011045	0.7765269	0.8020961
Subcell	0.8030392	0.7785268	0.8040281
Exact	0.7926823		

The simulation results using 99 uniform cells at initial time of our method and other two methods in [7] are presented in Fig. 1. The numerical results of our method are close to the exact solution. The locations of interface for every method are showed in Table 1. The location of our method is the closest to the exact solution.

Then, we choose the one dimensional heat conducting equation to test the validity of our method for heat conduction coefficient. The heat conducting equation is

$$\frac{\partial T}{\partial t} - \frac{\partial}{\partial x}\left(\kappa(x)\frac{\partial T}{\partial x}\right) = 0 .$$

The computational domain is [0, 1], and the material interface is at 0.5. The heat conducting coefficients on the left and right side are 1 and 10 respectively. We test example with the boundary condition as follows:

$$T(0,t) = 0, \quad T(1,t) = 1 .$$

With arbitrary initial value, the solution should be convergence to the stationary solution

$$T(x) = \begin{cases} \frac{20}{11}x & 0 < x < 0.5 \\ \frac{9}{11} + \frac{2}{11}x & 0.5 < x < 1.0 \end{cases} .$$

The simulation result using 99 uniform cells (the fiftieth cell is multi-material cell) is displayed in Fig. 2. The numerical result accords with the exact solution perfectly.

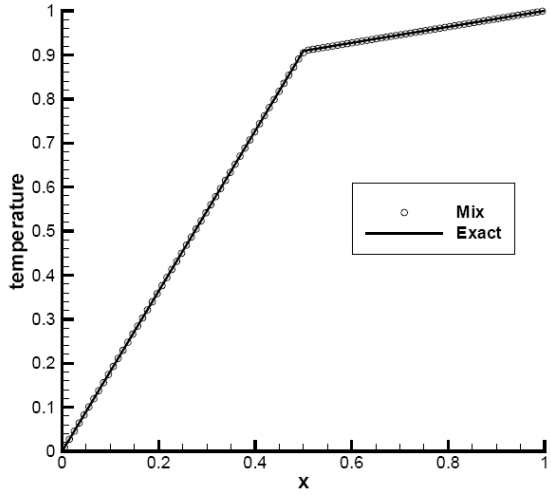

Fig. 2 Simulation results of steady stationary solution with discontinuous conductivity.

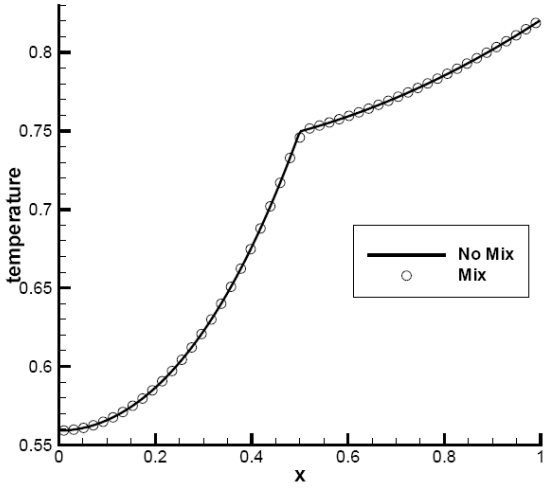

Fig. 3 Simulation results of source problem with discontinuous conductivity

Then we test the non-stationary problem with the

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boundary and initial condition as

$$\kappa \frac{\partial T}{\partial x}\bigg|_{x=0} = 0, \qquad \kappa \frac{\partial T}{\partial x}\bigg|_{x=1} = 2,$$

$$T(x,0) = 0.5, \qquad x \in (0,1)$$

The numerical results at t=0.1 are showed in Fig. 3, where the solid line is the results using 200 uniform cells and the circle is the results using 49 cells (the twenty-fifth cell is multi-material cell). The numerical results show that our method for heat conducting coefficient in multi-material cell is appropriate.

B. numerical results of ignition hohlraum

In order to show the current capability of our LARED-H code, we simulate the ignition hohlraum [1] of NIF. The length and inner radius of the columniform hohlraum is 9500 μm and 2750 μm. The material of hohlraum wall is Au and the mass density is 19.24 g/cc. The multi-layer implosion capsule lies at the center of hohlraum. The radius of capsule is 1110 μm. The capsule is separated to three layers, the outer layer is polyimide and the thickness is 160 μm; the middle layer is the main fuel DT ice and the thickness is 80 μm; the inner layer is DT air. The laser is injected the hohlraum in two rings from each laser entrance hole at opposite ends of the hohlraum. The wavelength of laser is 0.35μm and the energy is 1.35 MJ. The angles of incidence of inner and outer ring laser are 27.5° and 52.5° respectively. The proportion of energy between inner and outer ring is 0.5.

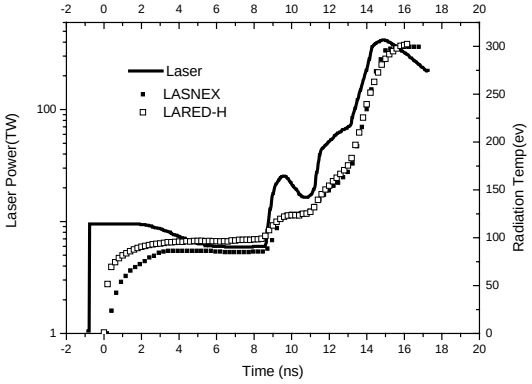

Fig. 4 Radiation temperature of ignition hohlraum.

We rezone the grids when the large distort problem occurs and lagrangian calculation is continued on the new grids. The multi-material cells are introduced at 10.4 ns. The radiation temperature inside the hohlraum is showed in Fig. 4. The solid line is the pulse shape of laser. The dot line is the results of LASNEX and the square line is our results. The radiation temperature accords at later time and the difference at early time comes from the difference of equation of state and radiation parameter. In our simulation, the energy absorbed by the capsule is about 160 KJ, and the corresponding value of NIF design is about 150 KJ [1]. The integrated simulation of ignition hohlraum shows the good performance of our LARED-H code.

V. Conclusion

The model of multi-material cell in Lagrangian step for radiation hydrodynamics is given in this paper. Using multi-material cells and arbitrary Lagrangian-Eulerian method, we overcome the multi-material large deformation problem and accomplish the integrated simulation of the ignition hohlraum. The satisfactory numerical results demonstrate the performance of LARED-H code.

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