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DEVELOPMENT OF TWO-DIMENSIONAL IMPLOSION CODE FOR LIB ICF

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In this paper we present a useful numerical method to solve a two-dimensional behavior of a fuel pellet in inertial confinement fusion. Example computations are also presented for an implosion phase of ICF pellet illuminated by light-ion beam.

Introduction

In inertial confinement fusion (ICF) one of the most important problems is to find a way to implode a fuel pellet in a spherically symmetric manner. In order to study the asymmetric implosion at least a two-dimensional computer code is required. Two-dimensional analyses have been also performed to study the assymmetric implosion. In addition three-dimensional computations have been also done. So far these researches about the nonuniform implosion have presented a limitation of nonuniformity amplitude in order to obtain a reasonable fusion output gain from a reactor size pellet; the reults show that only a few percent of the nonuniformity amplitude may be allowed for a direct-driven pellet. However, in an actual situation the amplitude of the nonuniformity may be larger than a few percent. We need some smoothing effects, like a radiation transportation or a geometrical smoothing effect. In this paper we present a useful numerical method to solve the two-dimensional behavior of a fuel in inertial confinement fusion.

Another problem in a multi-dimensional computation is a mesh distortion. A fuel density of an ICF pellet changes up to about a thousand times of the initial density in an implosion process. The change in radius (r) direction is most severe. In such a case we need the Lagrangian mesh in the r direction at least. If we also use the Lagrangian mesh in the azimuthal direction in a two-dimensional code, we must avoid a severe mesh distortion or a overlapping by using a resorning technique frequently. In order to avoid this, we developed a method in which the mesh velocity can be selected arbitrary, for example, the Lagrangian mesh is employed in the radial direction and the Eularian mesh is employed in the azimuthal direction. A Mixed-Eularian and Lagrangian (MEL) metho was previously developed in the x-y (or r-z) coordinate. In order to simulate the plasma sphere we developed our method in the spherical coordinate. Our method is focused on the MEL method in the spherical coordinate. However, the mesh velocity is basically arbitrary in our method as pointed out briefly. So we can select the mesh velocity to avoid the severe mesh distortion.

A useful numerical method presented in this paper is based on a three-temperature fluid model, which was presented in several previous papers. The physical base of three temperature model was also discussed previously in those papers.

Simulations examples are also presented for an imploding phase of a pellet in light-ion-beam (LIB) inertial confinement fusion (ICF).

Basic Equations and Numerical Method

The equations employed are the usual fluid equations to describe a plasma: The equations of conservations of mass, momentum and energy are as follows:

$$\partial\rho/\partial t+\nabla(\rho\mathbf{u})=0 \quad (1)$$

$$\partial(\rho\mathbf{u})/\partial t+\nabla(\mathbf{u}\rho\mathbf{u})=-\nabla P \quad (2)$$

$$\partial(\rho e_l)/\partial t+\nabla(\mathbf{u}\rho e_l)=-P_l\nabla\mathbf{u}+S_l \quad (3)$$

Here ρ is a mass density, t the time, u the velocity, P the total pressure, e the specific internal energy and S the source term including an energy transportation. Tha suffix l takes i, e and r for ion, electron and radiation, respectively. The model used in this paper is the three temperature model. Therefore Eq.(3) shows a set of three equations for ion, electron and radiation. The total pressure P in Eq.(2) is the sum of the pressure of ion, electron and radiation. The source terms are descried as follows:

$$S_i=-K_{ie}+I_i \quad (4)$$

$$S_e=H_e+K_{ie}-K_{re}+I_e \quad (5)$$

$$S_r=H_r+K_{re}, \quad (6)$$

where Kie and Kre are the energy exchange rates between ion and electron, and between radiation and electron, respectively. The electron and radiation heat conductions are shown by $H_l=-\nabla F_l$ (l=e,r), where Fl is a heat-flux. In addition, the source term includes the heat surce coming from outside the system concerned, for example, light-ion-beam deposition.

In order to solve these equations numerically, we use a control-volume method and integrate Eqs.(1-3) over a volume V whose surface is S moving with a velocity **w**. Then we obtain

$$dM/dt=-\int_S d\mathbf{S}(\mathbf{u}-\mathbf{w})\rho, \quad (7)$$

$$d\mathbf{P}/dt=-\int_S d\mathbf{S}(\mathbf{u}-\mathbf{w})\rho\mathbf{u}-\int_S d\mathbf{S}P, \quad (8)$$

$$dE_l/dt=-\int_S d\mathbf{S}(\mathbf{u}-\mathbf{w})\rho e_l-\int_V dVP_l\nabla\mathbf{u}+\int_V dVS_l, \quad (9)$$

where $M=\int dV\rho$, $p=\int dV\rho u$ and $El=\int dV\rho el$. If w=0, Eqs.(7-9) show the Eularian scheme and if **w=u**, the Lagrangian scheme. We simulate a part of a sphere, that is $(-\Delta\phi/2<\phi<\Delta\phi/2,\ 0<\theta<\pi/2)$. In the φ direction we assume no motion.

This control-volume method generally has a numerical error of Δθ and Δφ for a direction of velocity in the θ and φ directions, respectively. We can eliminate this error of Δθ in the azimuthal direction, if we modify Eq.(8) to an equation for an angular momentum L to solve u_θ.

$$d\mathbf{L}/dt=-\int_S d\mathbf{S}(\mathbf{u}-\mathbf{w})[\mathbf{r}\times(\rho\mathbf{u})]-\int_S \mathbf{r}\times(d\mathbf{S}P) \quad (10)$$

Only the angular momentum in the y direction Ly is solved.

$$u_\theta=r\omega=rL_y/I, \quad (11)$$

$$I=\int_V dV\rho r^2=\int_V \rho r^4\sin\theta\, dr\, d\theta\, d\varphi \quad (12)$$

where I is an inertial moment and ω an angular velocity. If one try to solve u_θ by Eq.(8) directly, one has a difficulty to define the azimuthal direction in the computational space which has usualy finite size in the azimuthal direction. However, we can clearly define the direction of the angular momentum Ly without any difficulty and ambiguity to find u_θ. Therefore we use Eq.(10) instead of Eq.(8).

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In the ϕ direction we have still the same kind of numerical error of $\Delta\phi$ as described above, though we assume that physical quantities are homogeneous in the direction. In order to minimize this error we should take $\Delta\phi$ to be less than $\Delta\theta$.

The mesh velocity w is arbitrary. However, for our purpose the Eularian mesh is appropriate in the azimuthal direction. Therfore we select now $w\theta=0$. In this ur is solved by

$$du_r/dt=[\partial/\partial t+w_r\partial/\partial r]u_r \quad (13)$$

$$=[-(u_r-w_r)\partial/\partial r-\omega\partial/\partial\theta]u_r+r\omega^2-\partial P/(\rho\partial r).$$

The left handside of the energy equation is rewritten by assuming that the physical quantities are constant in the small volume V of one mesh.

$$dE_1/dt=M(C_1dT_1/dt+B_1d\rho/dt)+e_1dM/dt, \quad (14)$$

where C1 is the specific heat and B1 is the compressibility. One can obtain C1 and B1 from an equation of state. We used a fitting formula to the SESAMI library as an equation of state. A data for the charge state includes the thermal ionization by the corona and Saha models, and pressure ionization by a fitting formula.

In order to obtain the explicit expressions for Eqs.(7-9), we specify wr to satisfy the Lagrangian condition in the r direction, though we use the Eularian mesh in the azimuthal direction. This means the introduction of the MEL method. The MEL method is appropriate for our purpose. In this special case wr should satisfy the following equation:

$$w_r=u_r-\omega dr/d\theta. \quad (15)$$

From this equation we find the mesh movement.

Application to Pellet Implosion Simulation in Light-Ion-Beam Inertial Confinement Fusion

In order to demonstrate a usefulness of this method for a two-dimensional analysi of a plasma sphere we preformed a numerical simulation for an implosion phase of an ICF pellet illuminated by light-ion beam.

A LIB-ICF pellet employed in this section in presented in Fig.2 and consisted of three layers of Pb, Al and DT.

Only the proton beam is considered as a LIB in this paper. A particle energy employed is 5Mev and the total energy of LIB impinging a pellet is 5MJ. The LIB pulse duration is 40nsec. The pulse rasing time is 15nsec and the beam power increases with a function of $(\text{time})^2$. During 15nsec and 40nsec the LIB power is constant and 167TW. After 40nsec the beam power is zero. The LIB energy deposition is computed by using equations for proton stopping power including the plasma effect. In this paper we assumed that all protons impinging the pellet surface normally.

The nonuniformity is introduced by changing the LIB number density as follows:

$$n=n_0+0.5n_0\delta[\cos(m\theta)-1], \quad (16)$$

where δ is the amplitude of nonuniformity and m the mode number.

Figure 3 presents implosion patterns in a 2mm square at time t=40nsec and 46.7nsec which is the void closure time. The solid mesh lines show the DT fuel and dashed lines the Al layer. The Pb layer is outside of this figure. In this example the amplitude of the nonuniformity is 6% and the mode number m is 2. The total mesh number employed in this example is 30 in each r and directions. Figure 4 shows ur of the innermost mesh in the r-t domain. Figure 4 shows that a part illuminated by a lower power relatively has a larger ur near the void closure time. This part is shown in Fig.3 as a depression. At the beggining stage of the implosion this depression part is compressed by a weak u_θ or a slight movement in the θ direction of a side part of this depression. Then the pressure increases at this part and the inner DT fuel near this part is accelerated inward like a jet as shown in Fig.4. We call this as a jet effect in this paper. This is the nature of a nonuniformity-imploding fluid shell and a kind of geometrical smoothing effect. A precise study of this jet effect is not a theme of this paper and should be presented in another work. Figure 5 presents peak-temperature profiles is the Al layer at t=40nsec as a function of θ; solid line shows a result in which a radiation transport is included in both the r and θ directions and a dotted line shows a result including a radiation transport only in the r direction. The solid curve presents a clean radiation smoothing effect in the direction. The nonuniformity is smoothed down to 0.9% at t=40nsec. At the beginning $t\simeq 0$ the nonuniformity was 6%. This radiation smoothing effect is major but a study about this is also not a theme of this paper. The precise reserch about the geometrical and radiation smooting effect will be discussed in the next work.

This simulation results for a pellet implosion in LIB ICF demonstrate that this numerical method presented in this paper is useful for the analyses of two dimentional behavior of a plasma sphere or a spherical shell.

Discussions

We developed a two-dimensional-numerical method to solve a behavior of plasma sphere or a spherical shell. We also presented example simulation results for an ICF pellet implosion illuminated by light-ion beam.

In this numerical method we could avoid a severe mesh distortion or mesh overlapping by introducing an arbitrary mesh velocity, though in this paper we described a MEL method as a special case. We also introduced a new dependent variable of angular momentum L to compute u_θ. By introducing L we eliminated a numerical error described in the second section.

The example simulation for a pellet implosion in LIB ICF demonstrated that this numerical method is useful to solve a two-dimensional behavior of a plasma sphere or a spherical shell.

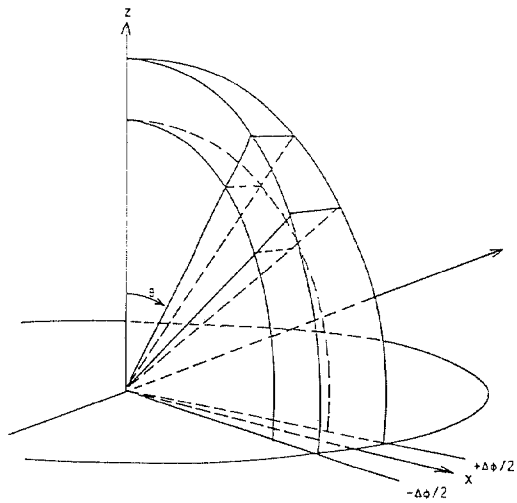

Fig.1 A computeational region for a plasma sphere or a spherical shell: $(0 \leq \theta \leq \pi/2, -\Delta\phi/2 \leq \phi \leq \Delta\phi/2)$. In order to solve u_θ an angular momentum Ly directing to the y direction is used.

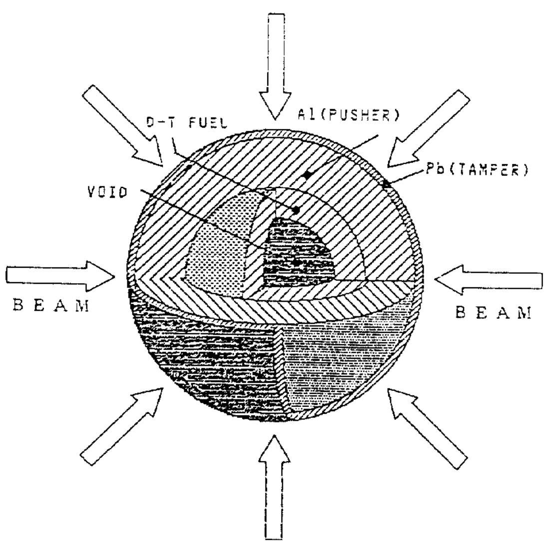

Fig.2 A pellet structure employed in the third section as an example. Light-Ion Beams impinge the pellet and deposit their energy mainly in Al and partly in Pb. The Pb behaves as a temper and the Al as a beam energy absorber. In addition an inner part of Al facing to DT fuel behaves as a pusher and a radiation shield.

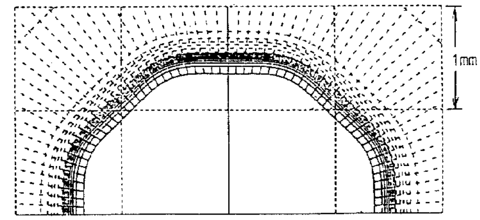

Fig.3 Implosion patterns inside a 2mm square at t=40nsec . Solid mesh lines show the DT fuel and dotted mesh lines Al. In this case the amplitude of nonuniformity is 6%.

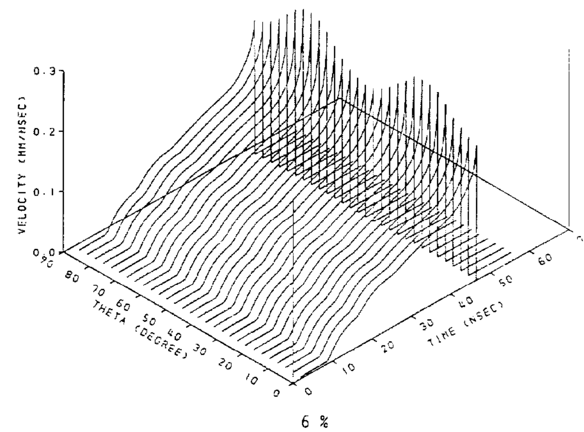

Fig.4 The radial velocity u_r of the innermost Lagrangian mesh. Near the void closure time a jet effect was observed.

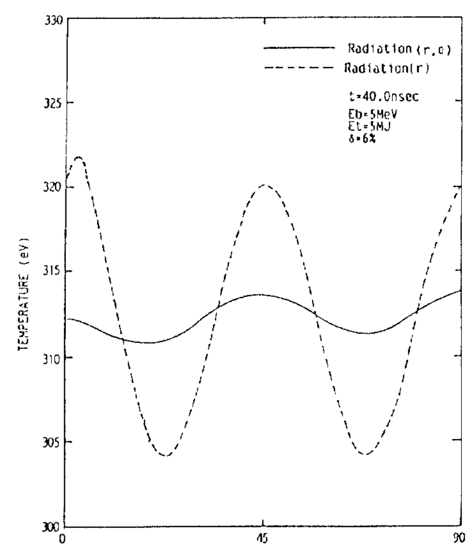

Fig.5 Peak temperature profiles in the Al layer at t=40nsec as a function of θ. A dashed line shows a result without the radiation transport in the θ direction but with it in the r direction. A solid line shows a result with the radiation transport in both the θ and r directions. The radiation transport smoothed the initial nonuniformity of 6% down to 0.9%.