Two-Dimensional Analysis of Energy and Momentum Deposition Effects of Alpha-Particles in ICF Plasmas

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Abstract. Two types of two-dimensional codes, *i.e.* a transport code and a diffusion one, have been developed for analysis of alpha-particle effects in ICF plasmas. On the basis of 2-D coupled transport/ hydrodynamic simulations, we investigate the energy and momentum deposition effects of alpha-particles on the Rayleigh-Taylor instability in a stagnating DT planar plasma. After the accuracy validation of the diffusion code, the sensitivity of fuel gain to the perturbation amplitude is also discussed by carrying out 2-D coupled diffusion / hydrodynamic simulations for a DT spherical target with mode number of l = 2 – 12.

1. Introduction

For theoretical study of complex phenomena such as implosion and burn of inertial confinement fusion (ICF) targets, a multi-dimensional code including all important physics of ICF is indispensable. Slowing-down and transport process of alpha-particles is one of the most essential phenomena in ignition and burn phase, so that accurate treatment of this process is required. In most of the multi-dimensional ICF codes, however, alpha-particle heating rate is calculated in a roughly approximated way. With regard to another important quantity, *i.e.* momentum deposition rate, few have been reported. Thus, the development of multi-dimensional alpha-particle "transport code" (numerically solving transport equation for angular flux), which accurately calculates the heating rate and the momentum deposition rate, are required for the detailed examinations, *e.g.* the alpha-particle effects on hydrodynamic instability in the stagnation phase or the role of alpha-particles in ignition and burn dynamics of fast-ignited targets. In full simulations using a multi-dimensional integrated code, however, the transport calculation for alpha-particles is not desirable because of the computation time, required size of computer memory and difficulty in applying to non-orthogonal frame. In this case, a "diffusion model" neglecting the angular dependence of particle flux would be practically adopted as a reasonable approximate method. As a matter of course, it is required for the diffusion model to accurately calculate the energy and momentum deposition rates.

Recently we have developed two types of two-dimensional (2-D) codes, *i.e.* transport code for detailed examination of alpha-particle effects and diffusion one for the purpose of coupling with 2-D integrated code ILESTA-2D [1]. In the present paper, we report the calculational models of two codes together with some results of coupled transport (or diffusion) / hydrodynamic simulation and demonstrate their usefulness.

2. Model Description of 2-D Simulation Codes

The following codes have been developed in 2-D planar (or cylindrical) coordinates system and written in the Eulerian mesh flame.

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2.1 Alpha-Particle Transport code

The transport code has been developed on the basis of time-dependent transport equation for charged particles where as the collision process of alpha-particle in the plasma, only small-angle Coulomb scattering is considered. The electromagnetic force term is neglected here. As for the numerical solution, the fully-implicit scheme and the discontinuous liner FEM method [2] are used for the time and the energy variables, respectively. For the angular and the position variables, the discrete Sn method [3] and the CIP method [4] are adopted. Using the angular flux Ψ (the solution of transport equation) and the Fokker-Planck (F-P) coefficients, the energy and momentum deposition rates are evaluated. These rates are incorporated into the hydrodynamic equations.

2.2 Alpha-Particle Diffusion Code

Our recent study in the framework of 1-D calculation [5] showed that the diffusion model based on the Levermore-Pomraning (L-P) theory [6] can accurately calculate the heating rate of alpha-particles and then is appropriate for ignition and burn simulations of ICF targets. Following the accuracy validation in 1-D model, we have extended this diffusion code to 2-D one. As for the numerical solution, the fully-implicit scheme and the multi-group method are used for the time and the energy variable, respectively. For spatial variables, a 9-point difference scheme developed by Kershaw [7] is adopted. The energy and momentum deposition rates in the diffusion model can be evaluated in the same way as that in the transport model. In this case, instead of the angular flux, the scalar flux (the solution of diffusion equation) is used.

2.3 Hydrodynamic Code

A hydrodynamic code was developed on the basis of 1-fluid 1-temperature model. In this code, the ideal gas model is employed for the equations of state. In equation of motion, the momentum deposition rate of alpha-particles obtained from transport (or diffusion) calculation is added. In equation of energy, electron thermal conduction, radiation effect and alpha-particle heating are taken into account. The radiation effect is evaluated by 1-group flux-limited diffusion model in the ignition and burn simulations (discussed in Sec.5). However, in the simulation for stagnation dynamics (in Secs.3 and 4), radiation was neglected to simplify the problem. These hydrodynamic equations are solved using the CIP method [4].

3. Energy and Momentum Deposition Effect in Stagnating Plasmas

In the final stage of compression (*i.e.* stagnation phase) of ICF, the boundary region between the spark and main fuel becomes Rayleigh-Taylor (R-T) unstable. The previous 2-D simulations [8], [9] showed that once the spark temperature becomes sufficiently high, the alpha-particle heating drastically smoothes the spark structure. On the other hand, it was mentioned that in some cases the momentum deposition of alpha-particles enhances the instability [10]. These two studies approximately treated the alpha-particle transport and did not consider the energy and momentum deposition simultaneously.

In order to estimate the effect of energy and momentum deposition of alpha-particles on the R-T instability in the stagnating plasmas, we carried out coupled transport/hydrodynamic simulations. Here, we assumed a 2-D planar D-T plasma with a spark/main fuel configuration as shown in Fig.1. At the start of the simulation, a sinusoidal single mode perturbation was applied to the contact surface. The initial wavelength was set as λ = 20, 40 and 80μm.

Figure 2 (a) [Fig.2 (b)] shows the temporal evolution of the perturbation width δ , the distance from the bubble head to the spike tip, when the initial width is small (δ_0 = 1.4μm) [large (δ_0 = 11μm)]. In the early stage of ignition when the spark temperature is lower than 20keV (t <130ps), the alpha-particles deposit their energy almost instantaneously and locally in the region where they are born, which means that the alpha-particle heating rate is small around the contact surface. As is found from Fig.2 (a) and (b), thus, the alpha-particles scarcely affect the temporal evolution of perturbation when t <130ps. Once the explosive ignition occurs in the spark region, the perturbation is significantly smoothed by alpha-particle heating, which is so-called alpha-particle's fire polishing effect [8, 9]. In the small perturbation cases (Fig.2 (a)), this fire-polishing occurs at the same timing among three cases independent of the wavelength. When the induced perturbation is so large as to grow into a non-linear phase during the stagnation, however, the shorter the wavelength is, the faster the timing of smoothing becomes (Fig.2 (b)). We also found that the momentum deposition slightly affects the temporal evolution of perturbation.

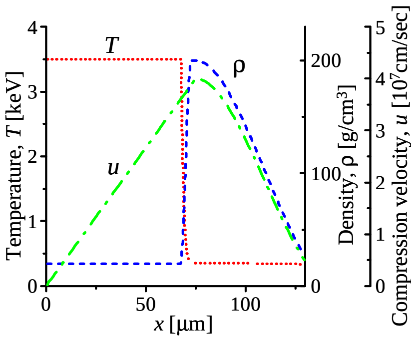

FIG.1. Initial non-perturbed profiles of temperature, density and compression velocity.

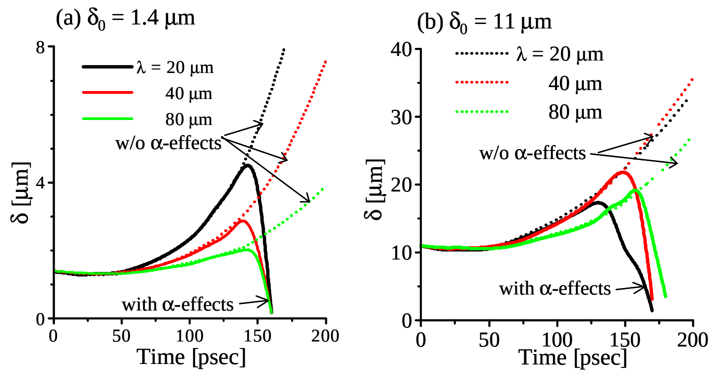

FIG.2. Temporal evolution of δ *when the initial perturbation amplitude is (a) small* (δ_0 = 1.4μm) *and (b) large* (δ_0 = 11μm).

4. Accuracy Validation of Diffusion Code

In massive simulations such as multi-dimensional implosion and burn simulations, the diffusion model is more reasonable than the transport one from the viewpoint of computational resource. In this section, the accuracy of our 2-D diffusion code is validated before applying it to examination of ignition and burn dynamics. We carried out the coupled diffusion/hydrodynamic simulations by assuming the same initial plasma conditions as employed in Sec.3, and then the code check was done by comparing the temporal evolution of perturbation obtained from the diffusion model simulations with that from the transport model ones.

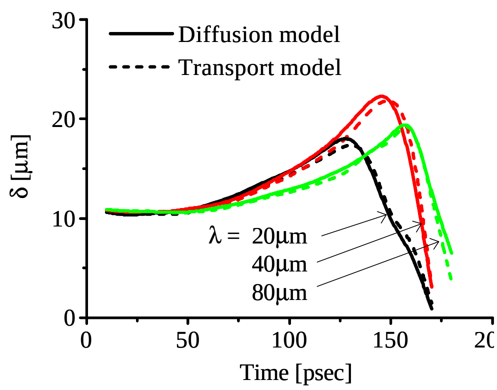

FIG.3. Comparison of temporal evolution of δ *between diffusion model simulations (solid lines) and transport model ones (broken lines) in the case of* δ_0 *= 11μm.*

In Fig.3, we show the temporal evolution of δ for the cases of λ = 20, 40, 80μm obtained from the diffusion model simulations and the transport model ones. The results of the diffusion model simulations are in close agreement with those of transport model simulations. Compared with the results of transport model simulations, however, the diffusion model somewhat overestimates the alpha-particle effects; the growth of perturbation is faster and the smoothing due to the alpha-particle heating occurs earlier. This is due to the difference in the profile of heating rate between the two calculation models. The L-P diffusion model slightly overestimates the heating rate around the contact surface compared with the transport model, as was pointed out in our previous 1-D work [5]. This difference leads to the deviation from the results of the transport model simulations. The momentum deposition profiles at the contact surface are also different between two models. However, as was stated in Sec.3, the momentum deposition slightly affects the R-T instability, so that this difference is not important.

It should be noted that the coupled diffusion/hydrodynamic simulations were carried out using a PC with Pentium III 700Mhz processor. In the case of 83×133 grids system and 180ps simulation, used CPU time and memory were about 10hours and 32MB. Compared with this, in the case of transport model simulation for the same calculation condition, the CPU time and memory were about 80hours and 740MB using a vector super computer (NEC SX-4).

It is concluded from these results that the diffusion model based on the L-P theory is reasonable to use as a module of an integrated code for the full simulation of ICF.

5. Effect of the Rayleigh-Taylor Instability on Ignition and Burn Properties

On the basis of 2-D diffusion/hydrodynamic simulations, we examined how the R-T instability at the contact surface between the spark and the main fuel regions affects ignition and burn properties of a DT spherical target.

As is shown in Fig.4, the simulation configuration is a half of the full system. It has cylindrical coordinates, symmetry along the y-axis and with respect to plane of y = 0. The simulation region is 380μm×380μm (200×200 grids), and the grid interval is set as $\Delta x = \Delta y =$ 1.9μm. The simulations are launched with such an initial state that the target is regarded to be in the early stage of stagnation where the fusion reaction is negligible. As initial radial profiles of temperature, density and pressure, we assumed a semi-isobaric configuration as shown in Fig.5. The total fuel mass is 3mg. The initial mass-averaged compression velocity is set as $\langle u \rangle(0) = 2.52\times10^{7}$ cm/sec, which is sufficient for ignition of the target in the non-perturbed case. At the start of the simulation, a sinusoidal single mode perturbation is applied to the density, temperature and velocity profiles around the contact surface located at r_c = 200μm.

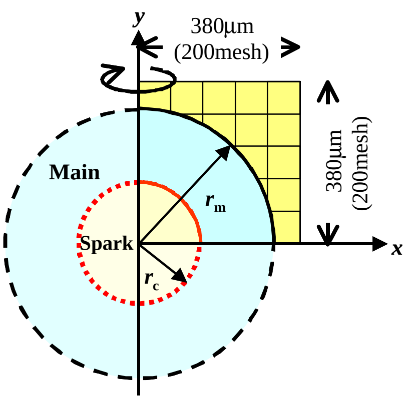

FIG.4. Simulation configuration.

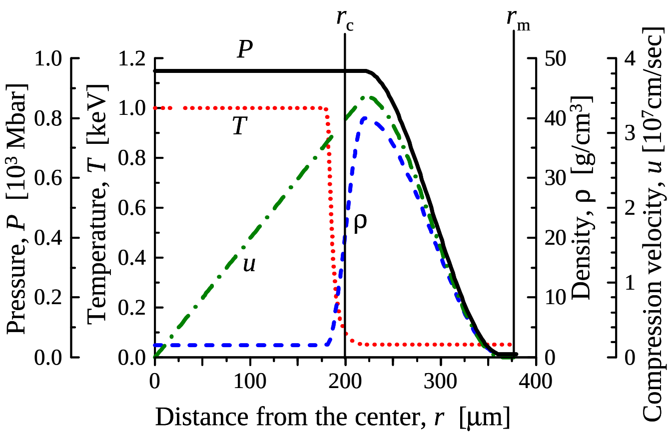

FIG.5. Initial non-perturbed radial profiles of density ρ, temperature T, pressure P and compression velocity u.

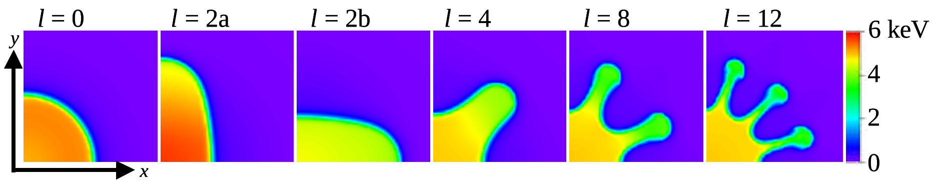

FIG.6 Temperature distributions at t = 400ps obtained from the simulations neglecting the energy transport due to electron conduction, radiation and alpha-particles

Before evaluating the ignition and burn properties, we examined the effect of perturbation on the spark formation by carrying out the simulations neglecting the energy transport due to electron conduction, radiation and alpha-particles. Figure 6 shows the temperature profiles at t = 400ps. In the case of l = 2a (distorted like a rugby ball), the core temperature and the density are higher than those in the non-perturbed case. Contrary to this, in the case of l = 2b (a disk-like distortion), corresponding values are the lowest among all the cases, although the core size is large. In the cases of mode number more than 4, the core size, density and temperature approach those in the non-perturbed case with increasing mode number.

Finally, we discus the ignition and burn properties. In Fig.7, the fuel gain obtained for each mode number is plotted as a function of the initially applied perturbation amplitude δ_0 / r_c. It is found that the margin of perturbation for achievement of significant gain (G > 1000) is the narrowest in the case of l = 4. In the cases of mode number more than 4, the margin becomes wide with increasing mode number. In the case of l = 2a, the margin is twice wider than that in the case of l = 4 because of high compression of the spark region. The margin of the perturbation of l = 2b is almost the same as that in the case of l = 8.

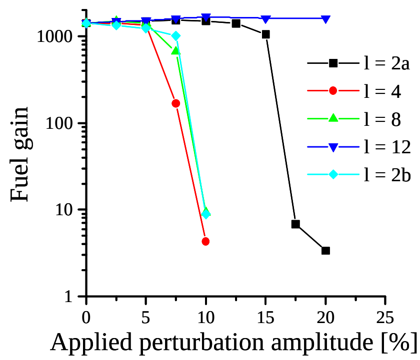

FIG.7. Fuel gain as a function of applied perturbation amplitude.

6. Concluding Remarks

We reported the alpha-particle's effect on the temporal evolution of perturbation in the stagnating planar plasmas on the basis of 2-D coupled transport/hydrodynamic simulations. In addition, by carrying out the diffusion model simulations for a DT spherical target with perturbations of l = 2-12, we showed the sensitivity of fuel gain to the initial perturbation amplitude.

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