High-density implosion via suppression of Rayleigh–Taylor instability

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Abstract. Radiation hydrodynamic simulations of ICF capsules assuming a kJ-class laser facility were conducted to evaluate the hydrodynamic stability of a brominated plastic shell. An opacity table based on a detailed atomic model was employed so that more quantitative forecast of the implosion dynamics could be performed. A lightly doped shell could form a high-density core at the maximum compression by suppressing the hydrodynamic instability.

1. Introduction

Until today, inertial confinement fusion (ICF) has not generated the extra amount of energy because implosion asymmetry induced by Rayleigh–Taylor instability (RTI) fails to ignite a thermonuclear fuel. The RTI prevents from obtaining the ICF energy mainly in two ways. First one is contamination of the hotspot by higher-Z elements [1]. Perturbation is seeded on the gas/solid interface of a thermonuclear fuel at the acceleration phase; then it is amplified by the RTI on the deceleration phase. Thus, the hotspot is contaminated by higher-Z elements included in the ablator, resulting in a reduction of hotspot temperature due to radiation cooling. Second is reduction of density–radius product \( \rho R \) which regulates the thermonuclear chain reaction [2].

A number of investigations on the ablative RTI have been conducted in theoretical [3, 4, 5] and experimental [6, 7] manners. One of the most famous outcomes of linear stability analysis is so-called modified Takabe formula [3, 4]:

\[
\gamma(k) = \alpha \sqrt{\frac{kg}{1 + kL}} - \beta kv_a, 
\]

where \( \gamma \) is the linear growth rate for the wavenumber of \( k \), \( g \) the acceleration, \( L \) the density scale length of an ablation front, \( v_a \) the ablation velocity, \( \alpha \) the square root of Atwood number, and \( \beta \) a fitting parameter for the ablative stabilization. A high-Z doping scheme [7] was proposed to suppress the ablative RTI. Emission from the high-Z ions may enhance \( v_a \) in the case of the direct-drive, so it is expected that the RTI is suppressed according to Eq. (1).

In this study, we investigated whether a brominated plastic shell can suppress the RTI and can achieve greater \( \rho R \) than the non-doped one. Implosion dynamics with a large non-uniformity...
of the incident lasers was studied to evaluate the effect of suppression of the RTI. The temporal profile of $\rho R$ was then analyzed to discuss the mechanism that the high-Z doping can enhance $\rho R$ at the maximum compression. Moreover, robustness of the high-Z doped target for the hydrodynamic instability was investigated by 2D parametric study.

2. Numerical methods and conditions

Numerical simulations in this study were conducted with a radiation hydrodynamic code, RAICHO [8]. Governing equations are discretized in $(r, \theta)$ coordinates whose pole is an axis of rotation. Implosion dynamics was described by Euler equation with energy sources and energy equations for ions and electrons. Laser energy was deposited on the electrons by one-dimensional ray-tracing in the radial direction with free–free absorption coefficient. Thermal conduction was approximated by the flux limited diffusion (FLD) manner with Spitzer–Härm conductivity [9]. The flux limiter of FLD was set to 0.1. Radiative transfer equation was reduced to the multi-group diffusion form with variable Eddington factor of Minerbo [10]. Atomic process of bromine ions was calculated by HULLAC code [11] which is based on the detailed configuration accounting (DCA) model, and opacity table was composed by JATOM code [12] with collisional radiative (CR) model. Although the DCA can generate the better opacity table than the average-ion (AI) model, the HULLAC code cannot handle low-Z plasmas. Thus, the opacity was calculated by the AI and CR models for hydrogen and carbon ions.

Schematic of the shell target is shown in Fig. 1. The ablator was composed of polystyrene (CH) or 0.05%-doped brominated one (CHBr). In order to simulate the laser incidence of GEKKO-XII, the pulse shape was set like Fig. 2. The pulse energy was 2.5 kJ, the pulse width was 1.3 ns in full width half maximum, and the wavelength was 527 nm. The shell surface was genuinely spherical, and perturbation was added in the angular distribution of the incident laser as following;

$$\delta a/a = (\delta a/a)_{\text{max}} \cos(l\theta), \quad (2)$$

where $\delta a/a$ is the ratio of the perturbation to the uniform component. The wave mode $l$ was set to 32 in this paper. Note that this is not a fundamental wave in the axial symmetric $(r, \theta)$ coordinates, i.e., the Legendre mode perturbation. Computational domain $D$ was set as the below expression;

$$D = \{(r, \theta) \mid 0 \leq r \ [\mu m] \leq 300, \ 0 \leq \theta \leq \pi/2\}. \quad (3)$$
The domain $D$ was partitioned into computational cells which have the equal interval in the $(r, \theta)$ space. The numbers of grids were 513 in the radial direction and 257 in the polar one. Boundary condition was the outflow condition at $r = 300 \mu m$ while the others were the mirror boundaries.

3. Results

Figure 3 shows the implosion dynamics of the CH and CHBr shells. At the beginning of acceleration (Figs. 3(a) and 3(b)), density of the CHBr is less than the CH since bromine ions emit high-energy photons and preheat inner side of the shell. Additionally, amplitude of the perturbation is not different so much between them, so the capability to suppress the RTI can be estimated by the perturbation growth after this time. Figures 3(c) and 3(d) suggest that the CHBr target shows shorter length of the spike than the CH one, and the inner wall of the CH is completely broken. As a result, only the CHBr target could result in high-density core at the maximum compression (Figs. 3(e) and 3(f)).

Figure 4 depicts the temporal profile of $\rho R$ with the amplitude of $\delta a/a = 10\%$. The CHBr target achieved nearly twice greater $\rho R$ than the CH one. Note that the two peaks of $\rho R$ was found for the CH target at $t = 2.5$ and 2.65 ns. This phenomenon corresponds to the Bubble–spike (BS) structure generated by the RTI. When the BS structure is developed like Fig. 3, a reflected shock wave is generated at the inner wall of the target. Thus, the first peak corresponds to the shock compression. The CH target has longer spikes than the CHBr one, so the shock compression arrives at the earlier time. On the other hand, the second peak corresponds to the stagnation of the massive region. The CHBr target has a stationary point around $t = 2.65$ ns, while the CH one has the second peak at the same time. This is because the acceleration of both targets seems to be the same for such a lightly doped case. Hence, it is important to shorten the time interval between the shock compression and the stagnation in order to generate a high-density core.

Moreover, we conducted a parametric study to obtain the dependency of $\rho R$ on the amplitude of laser non-uniformity. Figure 5 shows the maximum $\rho R$ obtained by the 2D simulations except the 1D simulations for the uniform case. At the cases of nearly uniform, the CH target has higher $\rho R$ than the 0.05% doped one, and the 0.3% one has lower $\rho R$ than the CH target at the most perturbed case. This is because strong emission from the bromine ions preheats the shell and compression at the stagnation is weaken due to the higher adiabat. Therefore, brominated targets should not be used if the hydrodynamic instability is not the most crucial cause to spoil the maximum $\rho R$. Laser non-uniformity of GEKKO-XII seems to be several tens of percent, so the high-Z doped target might support the core generation.

4. Conclusion

RHD simulations of ICF implosions were conducted to analyze the hydrodynamics of a brominated shell. In our previous work, opacity tables were generated with the AI model which is one of the most primitive models for atomic process. The simulations with the DCA opacity revealed that the lightly doped target can suppress the RTI resulting in the core generation at the maximum compression. In the case of large perturbation, the CHBr shell achieved greater $\rho R$ because the time interval between the shock compression and stagnation was shortened. The brominated target has more robust characteristics for disturbance while the 1D performance is inferior due to the higher adiabat. However, intensity of the lasers on this study is sub-ignition class which is much less than the mega-joule class reactor. There are some arguments that the RTI can not be suppressed with mid-Z ablators in the ignition-relevant implosion [13]. It is our future work to demonstrate that the high-Z doping scheme is available in such a scale.
Figure 3. Density contours of simulations with perturbation amplitude of $\delta a/a = 10\%$. Panels consist of (a) CH and (b) CHBr at the beginning of acceleration ($t \approx 2.1$ ns), (c) CH and (d) CHBr at the end of acceleration ($t \approx 2.5$ ns), and (e) CH and (f) CHBr at the stagnation phase ($t \approx 2.6$ ns).

Figure 4. Temporal profile of $\rho R$ for $\delta a/a = 10\%$. $\rho R$ was averaged over the polar direction.

Figure 5. Dependency of $\rho R$ at the maximum compression on the laser non-uniformity.

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