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Numerical study of the RT mixing in the deceleration phase of an implosion

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Abstract

The mixing of a stratified cylindrical shell in the deceleration phase of an implosion is numerically studied using a hybrid method combined with the weighted essentially non-oscillatory shock-capturing method and the tuned center difference scheme. The implosion histories with various premixing and initial distortion have been simulated. The results show that the growth rate of the mixing zone and the atomic mixing degree are sensitive to the premixing thickness. And calculations predict increased RT spike growth for the distorted shell.

Introduction

The Rayleigh-Taylor (RT) instability occurs whenever a heavy fluid is supported above a light fluid in a gravitational field, or whenever a light fluid against and accelerates a heavy fluid. Rayleigh-Taylor instability plays an important role during multiple phases of inertial confinement fusion (ICF) capsule compression. Initially, as the capsule is ablatively accelerated, the shell's outside is RT unstable. As the perturbations on the surface grow they deform the shape of the implosion away from the desired sphericity. Later, dense material decelerates rapidly as it stagnates at the center of the compressed capsule. In this phase of the implosion, the inner surface of the compressed shell is susceptible to the RT instability. RT growth during either the acceleration or deceleration phases of an ICF implosion can result in decreased ICF gain.

We have developed the capability to perform high-resolution simulations for RT, RM and KH instabilities and the induced turbulent mixing. In this paper we use a simplified cylindrical shell model to study the RT mixing in the deceleration phases of an implosion. And we discussed the effects of premixing and the shell's initial distortion on the mixing growth.

Equations of Motion

The simulations presented here are performed using our code HIME, which is a high-resolution multi-fluid Eulerian parallel hydrodynamic code. The equations governing the mixing of the miscible fluids are the N-species Navier-Stokes equations as follows,

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u_i}{\partial x_i}=0 \qquad (1)$$

$$\frac{\partial \rho u_i}{\partial t}+\frac{\partial\left(\rho u_i u_j+p\delta_{ij}\right)}{\partial x_j}=\frac{\partial \sigma_{ij}}{\partial x_j}+\rho g_i \qquad (2)$$

$$\frac{\partial E}{\partial t}+\frac{\partial (E+p)u_j}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\kappa\frac{\partial T}{\partial x_j}\right)+\frac{\partial \sigma_{ij}u_i}{\partial x_j}+\rho g_i u_i \qquad (3)$$

$$\frac{\partial \rho\varphi_i}{\partial t}+\frac{\partial \rho\varphi_i u_j}{\partial x_j}=\frac{\partial}{\partial x_j}\left(\rho D\frac{\partial \varphi_i}{\partial x_j}\right) \qquad (4)$$

where ρ is density, P is pressure, u_i is velocity, and T is temperature. The energy per unit mass, E, is related to the velocities and pressure by

$$E=\frac{P}{\rho(\gamma-1)}+\frac{1}{2}u_{ii} \qquad (5)$$

$$\sigma_{ij}=\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial u_k}{\partial x_k}\right) \qquad (6)$$

where σ_{ij} is the viscos stress tensor, μ is the dynamic viscosity, κ is the heat conduction coefficient, and D is the mass diffusivity.

Numerical Methods

In this study we used a TCD-WENO scheme developed by Hill and Pullin[1]. The TCD-WENO is a hybrid method combining the TCD stencil with a weighted essentially non-oscillatory (WENO) method[3]. The WENO scheme is used to capture moving discontinuities such as shock waves and contact surfaces, while the TCD scheme is used in smooth regions or turbulent regimes. The user-specified, optimum WENO weights are chosen to match those of the TCD scheme. It is expected that these weights will be achieved automatically in regions of smooth flow away from shocks, but in practice a switch is found to be necessary. The hybrid TCD–WENO scheme is shown to work well for unsteady gas-dynamic flows in one and two dimensions.

The fluxes of the viscos and diffusion transport terms are computed using explicit center-difference operator. And we use a third order strong-stability preserving Runge-Kutta scheme for the time integration.

Imploding Model

To study the mixing growth in the deceleration phases of an implosion, we calculated a simplified cylindrical shell model as follows. The initial velocity field is set to make the shell to move quasi-isentropically. Figure 1 shows the location of the shell's profiles, and figure 2 is the acceleration of the shell's inner surface versus time. It can be seen that the shock wave is very weak in this imploding model. So the motion maybe considered as a quasi-isentropic compression. During the deceleration regime, the RT instability occurs at the inner surface. We used diffused surface in this paper. That is, there is premixing on the inner interface.

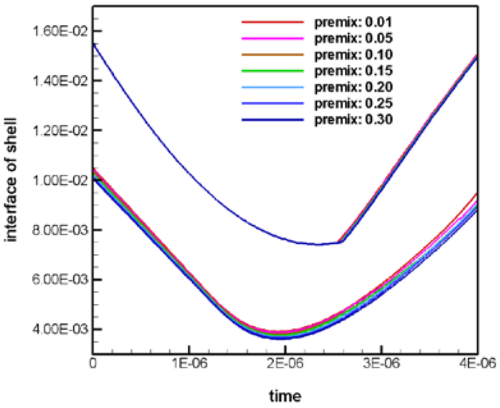

Figure 1. Location of the shell's inner and outer surface

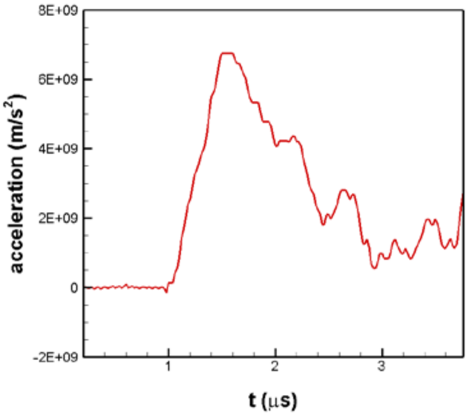

Figure 2. Acceleration of the shell's inner surface

Simulation Results

To study the effect of the initial premixing, we calculated a serious of cases with different thickness of premixing. In figure 1, the location of shell's profiles, we see almost the same results for different cases. This means the premixing has little effect on the shell's motion.

Figure 3 shows the evolution of density field in two cases. It shows little difference between the two cases. But for the mixture fraction, shown in figure 4, we can see obvious difference.

For the growth rate of the mixing zone, we can see that the premixing will reduce the mixing's growth rate during the deceleration regime. Figure 5 gives the thickness of the mixing zone vs. time.

Besides the growth rate, we also investigated the atomic mixing degree within the mixing zone. In figure 6, the parameter, mixing fraction, is used to measure how the two fluids are mixed. For this index, 1 corresponds to fully atomic mixing, while zero indicates that there is no atomic mixing, even if the two fluids penetrates to each other. We can see that the premixing can increase the atomic mixing degree.

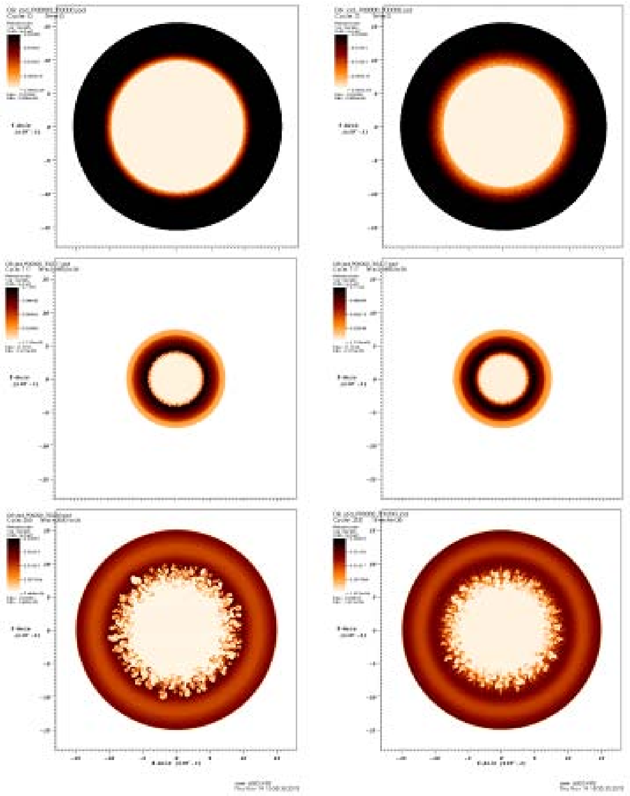

Figure 3. Evolution of the density field with various premixing thickness

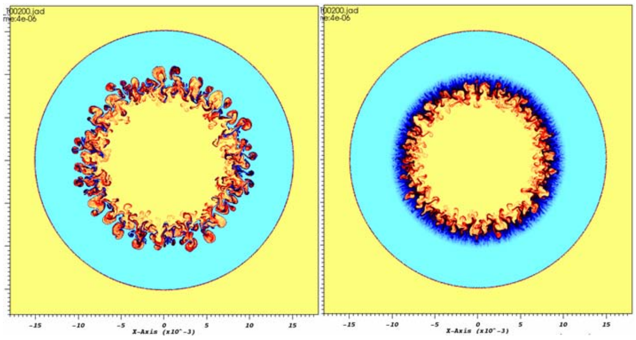

Figure 4. Mixture fraction with various premixing thickness

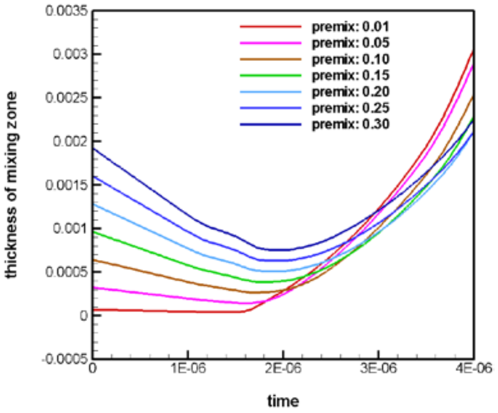

Figure 5. Thickness of the mixing zone vs. time

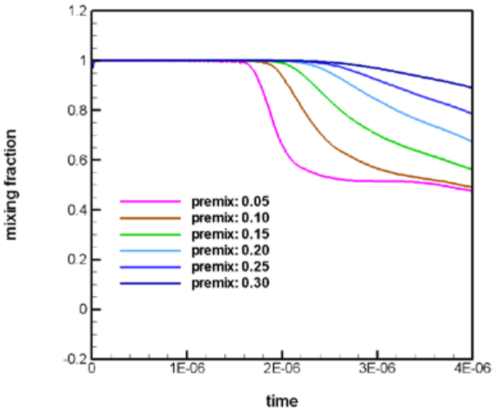

Figure 6. Mixing fraction vs. time

To study the effect of the initial distorsion, we simulated a shell as in figure 7. All the simulation parameters are the same, except the shell's initial shape. Figure 7 shows the evolution of the density field during the whole imploding and rebound motion. Figure 8 shows the difference between the shells with and without distortion at three typical moments.

It can be seen that the “spike” and “bubble” structures evolve quickly due to the RT instability on the inner surface during the deceleration regime. Long “fingers” emerge as the shell stagnates at the center. And when the shell rebound outwards, it is almost broken up.

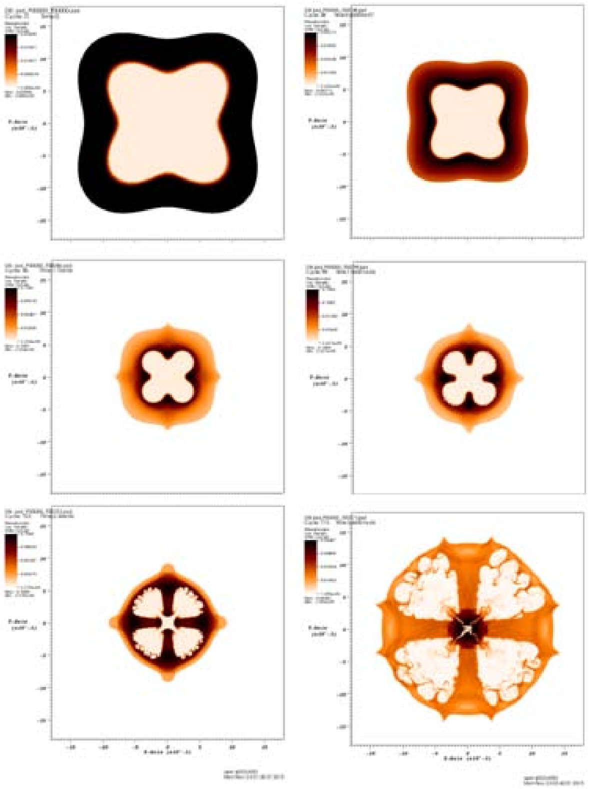

Figure 7. Density field of the distorted shell

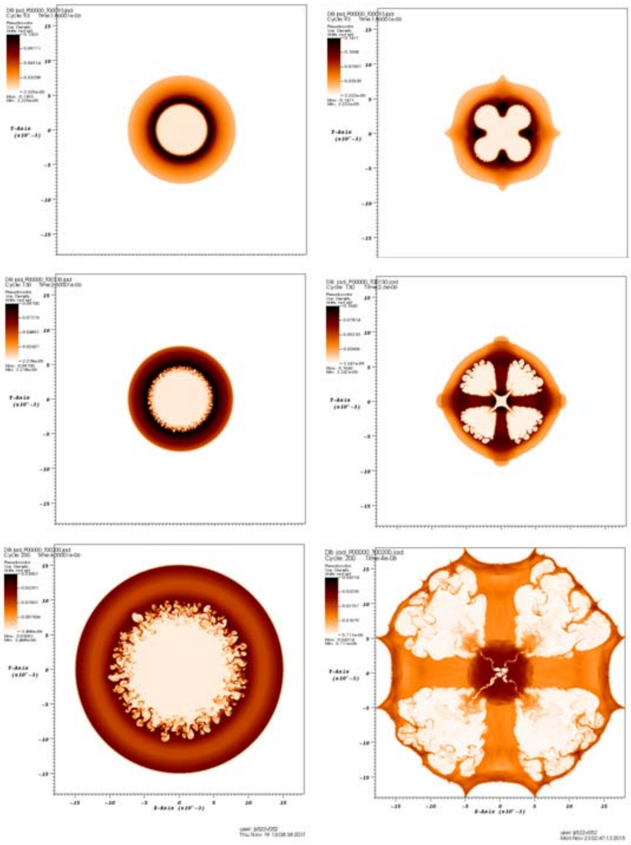

Figure 8. Comparison between two shells with and without distortion

Conclusions

We developed the capability to perform high-resolution simulations for RT, RM and KH instabilities and the induced turbulent mixing. A simplified cylindrical shell model is proposed to study the RT mixing in the deceleration phases of an implosion. We have discussed the effects of the initial distortion and the premixing. The results show that the growth rate of the mixing zone and the atomic mixing degree are sensitive to the premixing thickness. The premixing reduced the mixing growth and increased the atomic mixing degree. And calculations predict increased RT spike growth for the distorted shell.

Acknowledgments

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