Plasma viscosity in spherical ICF implosion simulations

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Abstract. Inertial confinement fusion (ICF) hydrodynamic codes often ignore the effects of viscosity though recent research indicates plasma viscosity and mixing by classical transport processes may have a substantial impact on implosion dynamics. A Lagrangian hydrodynamic code in one-dimensional spherical geometry with plasma viscosity and mass transport, and including a three temperature model for ions, electrons, and radiation treated in a gray radiation diffusion approximation, is used to study differences between ICF implosions with and without plasma viscosity and to examine the role of artificial viscosity in a Lagrangian implosion simulation. It was found that plasma viscosity has substantial impacts on ICF shock dynamics characterized by shock burn timing, maximum burn temperatures, fuel compression, and time history of neutron production rates. Plasma viscosity reduces the need for artificial viscosity to maintain numerical stability in the Lagrangian formulation and this study suggests that artificial viscosity may provide an unphysical stability in implosion simulations.

1. Introduction

Direct drive inertial confinement fusion (ICF) refers to laser heating of a spherical shell that contains fusion fuel, resulting in compression and fusion [1, 2]. Species plasma viscosity is usually assumed to be negligible [1] and may be overwhelmed by artificial viscosity used in many Lagrangian-based hydrodynamic codes for numerical stability and to capture the shock discontinuities. Recently, the role of plasma viscosity in smoothing small scale fluctuations in 2D ICF simulations has been reported [3]. Plasma viscosity and diffusion have been shown in 2D simulations to play a significant role in attenuating RT and KH interfacial instabilities for ICF relevant conditions [4]. These studies suggest that plasma dissipative processes are important at micron scale lengths for ICF relevant conditions. In a study examining plasma viscosity [5], it was found that the plasma viscosity in conditions relevant to ICF is likely to be important in degrading implosion performance. Computational studies examining plasma viscosity in ICF were summarized in [6].

2. Computations

We explore the dynamic effects of viscosity on ICF implosions through the use of a one dimensional, three temperature, Lagrangian hydrodynamics model that includes plasma viscosity and a self-consistent plasma mass transport [7] for treating fuel-plastic mass mixing. The present study focuses on ‘Omega-facility’ ICF experiments with simplified capsules of a CH shell and a deuterium fuel region. Lagrangian hydrodynamic equations model the mixture averaged quantities, and distinguish $T_i, T_e$ and a grey-body approximation to the radiation temperature, $T_r$. A radiative diffusion coefficient uses a simple fit to approximate tabular data for Rosseland averaged opacity.
The viscous stress tensor in spherical coordinates simplifies in 1D with the implied symmetries, \( u_\theta = u_\phi = 0 \) and \( \partial / \partial \theta = \partial / \partial \phi = 0 \). Evaluating the divergence, \( \nabla \cdot u = (1/r^2) \partial (r^2 u) / \partial r = \partial u / \partial r + 2u / r \), and for \( u \equiv u_r \), the radial component of the viscous stress is

\[
(\nabla \cdot \tau)_{r}[1D] = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{A}{3} \eta_o \left( \frac{\partial u}{\partial r} - \frac{u}{r} \right) \right) + \frac{4 \eta_o}{3r} \left( \frac{\partial u}{\partial r} - \frac{u}{r} \right)
\]

These four terms are interpreted as a diffusion of velocity, a compressible correction to the diffusion, a spherical metrics correction and the compressible contribution to the spherical coordinate correction.

The form for viscous dissipation in the energy equation with the assumed radial symmetry, \( [u_\theta = u_\phi = \partial / \partial \theta = \partial / \partial \phi = 0] \), becomes

\[
\Phi_{visc} = \eta_o \left( 2 \left( \frac{\partial u}{\partial r} \right)^2 + 2 \left( \frac{u}{r} \right)^2 \right) + \frac{2}{3} \left( \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 u)^2 \right)
\]

The numerical scheme is based on a standard Lagrange methodology with velocity evaluated at mesh cell faces or nodes, located between thermodynamic quantity cell centers. The three temperatures are updated semi-implicitly through an iterative procedure until converged at each time step. The 3T model was first tested in a 0-D model, the hydrodynamic and plasma physics underwent extensive testing as a cell faces or nodes, located between thermodynamic quantity cell centers. The three temperatures are updated semi-implicitly through an iterative procedure until converged at each time step. The 3T model was first tested in a 0-D model, the hydrodynamic and plasma physics underwent extensive testing as a one temperature code and then in the 3T version. Details of the model, numerical methods, and testing are provided in [6] and references therein.

3. Results
An ICF implosion of a plastic, CH, capsule of 25 micron thickness with inner radius of 400 microns imploding on a DD fuel was selected to validate the 1D code model and algorithms. The direct-drive laser power is 22 TW with an absorption fraction (default set to 60\%) delivered to the electrons in the outer CH zones over a 1 ns square pulse assumed to be representative of an Omega-scale ICF implosion. Setup details were previously described [6] and ICF test results from the code were found to be in reasonable agreement with the HELIOS ICF code [8].

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A radius-time plot of the Lagrangian interface between the fuel and plastic capsule is shown in Fig. 1(a) for the inviscid and for the viscous solutions and for a third case, where the plasma viscosity is on, and the artificial viscosity is turned off (labelled VISCwQavOFF_150607) immediately after the main shock converges on center (\( t \approx 1.496 \)). Figure 1 also shows surfaces on a log scale for plasma density for these three cases: (b) inviscid (artificial viscosity is ON), (c) viscous (plasma viscosity and artificial viscosity are ON), and (d) plasma viscosity is ON with artificial viscosity turned OFF after first shock convergence. In the density plots, the maximum values follow a 'ridge' showing the location of the innermost layer of the plastic capsule as it undergoes compression in each case. While artificial viscosity, \( Q_{av} \), is essential for Lagrangian numerical stability at early times, we find that once the entire domain becomes an ionized plasma (after the shock convergence at center) then the simulations can proceed with the plasma viscosity as the only dissipative mechanism and artificial viscosity is not needed for numerical stability. The capsule convergence for the viscous cases are less than the inviscid case (about 6\% in radius or 20\% in volume).

The incoming shock front is sharp in the inviscid case and remains so after convergence on center and during subsequent reflections in the fuel. The viscous shock has a less distinct density front location as it converges on center and after reflection. The time of shock arriving at center is approximately 0.1 ns later for the viscous case than the inviscid. With artificial viscosity turned off after shock convergence, there is considerably more wave structure or fluctuations in the 1D density solutions during compression. Zeroing out the artificial viscosity does not appear to greatly modify the 1D compression as seen in Fig.1(a), however, it is hypothesized that the increased fluctuations, apparent in the absence of artificial viscosity, lead to increases in entropy which will reduce implosion efficiency in the full 3D geometry.

The plots of burn weighted temperatures and the neutron production rates in Fig. 2 illustrate the key differences in shock timings between the inviscid and viscous cases. The calculation of burn weighted ion temperatures in Fig. 2 (a) shows for each case that the burn weighted ion temperatures exhibit two local maximum values, at the times of shock heating and compression burn. The maximum burn weighted ion temperature in the inviscid case is approximately 7 keV, while the viscous case maximum burn weighted ion temperature is about 3 keV, at first shock or at maximum compression. The difference between viscous and inviscid cases is large only during the first shock convergence and reflection from the center. The time averaged burn weighted temperature in either case was similar, about 2.6 keV, and comparable to experimental results and other 1D ICF simulations [8, 9]. Neutron production rates verses time in
Figure 1: Radius of the fuel-capsule interfaces near time of maximum compression for three cases (a). Plasma density surfaces in radius-time for Lagrangian artificial viscosity only (b), with plasma viscosity added (c), and with plasma viscosity ON and artificial viscosity OFF after shock convergence (d).

Fig. 2 (b) exhibit a local maximum value at the time of compression burn. During shock heating, neutron production is about 10% of the maximum for the inviscid case and significantly less for the viscous case, attributed to the low density at shock arrival time.

Figure 2: Burn weighted ion temperature (a) and neutron production rates (b) over time for both cases, viscid and inviscid.
4. Summary

A one dimensional staggered grid Lagrangian hydrodynamic code with a three temperature model for ions, electrons, and radiation was written to include plasma transport with viscous diffusion of momentum, viscous heating of ions, and species mass transport, in addition to thermal conductivities and temperature coupling through collisions. The code was used to examine ICF implosions typical of 'Omega-scale' direct-drive DD-CH fuel-capsules and it recovers reasonable results compared to experiments and to other codes for this class of ICF implosions. Overall, our examination of viscosity in ICF implosions, shows the plasma viscosity and viscous heating of the ions resulted in differences in maximum fuel compression, neutron production rate, and the time dependent burn weighted ion temperatures, with additional detail in [6].

We examined differences in results for simulations with or without plasma viscosity, and also in the viscous case with artificial viscosity turned off after shock convergence. The timing of the first shock on target center agrees with previous work [2, 8] and shows a timing lag ($\approx 0.1$ns) in the viscous case. The neutron production rate and the maximum and burn weighted ion temperatures are consistent with expected results [9, 10]. The ion temperatures are consistently higher for the inviscid case at first shock convergence by a factor of approximately two and it follows that the neutron production rate is augmented during shock convergence. The time averaged burn weighted ion temperatures agree within a few percent, and the neutron yields are comparable during compression between inviscid and viscous cases.

The minimum fuel radius during compression for the viscous case is greater by 6%, compared to the inviscid case. This corresponds to a 20% increase in fuel volume for the viscous case, and combined with a slightly wider mix width for the viscous case there is a 40% increase in the mix volume for the viscous case [6]. It is evident from the results that viscous effects cause a decrease in the compression.

After the first shock converges, the entire region is ionized and thus plasma viscosity is significant. After that time, the plasma viscosity and viscous dissipation eliminate the need for artificial viscosity to stabilize the numerics, and the artificial viscosity can be turned off. Results show that the subsequent solutions introduce greater shock-wave fluctuations in density (and in kinetic energy, temperatures and pressure) within the fuel and especially in the capsule material compared to cases when artificial viscosity and its corresponding energy dissipation are included. Eulerian methods can also introduce numerical dissipation and may present similar limitations when trying to accurately model physical viscosity in a shocked plasma.

Viscosity influences shock timings, fuel compression, neutron production rates, and heat fluxes especially at the time of first shock convergence. Viscous effects during the later compression phase appear to be small in this 1D example, but are likely to play a more important role in 2D and 3D as suggested in previous studies [3, 4]. It is expected that viscosity and plasma species mass transport will have a significant influence in other ICF implosions.

Acknowledgments
Los Alamos National Laboratory is operated by Los Alamos National Security, LLC for the U.S. Department of Energy NNSA under Contract No. DE-AC52-06NA25396.

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