A hybrid (ablation-expansion) model for low-density foams

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Abstract

Laser-foam interaction is described by a standard set of macroscale hydrodynamic equations coupled with a microscopic model accounting for the laser absorption in the solid foam elements and the subsequent foam homogenization. In the microscale model, each foam pore is divided into a cylindrical foam element and a low-density ablated plasma background. The movement of the cylinder boundary is controlled by the self-similar expansion while the mass transfer to plasma region is given by a stationary ablation model. Ordinary differential equations for the temporal advancement of the state variables are solved on the microscale and connected to the macroscale hydrodynamics using the conservation of mass and energy. The cross-section for laser deposition and scattering is calculated according to the Mie theory of electromagnetic scattering on cylindrical particles of sub-wavelength size.

Introduction

Low-density foams have a wide variety of applications in the fields of inertial confinement fusion and high energy density physics. However, direct simulations of laser propagation through a foam are difficult due to the large separation of scales, given by the necessity to spatially resolve the density differences in the foam microstructure. Unfortunately, low-density foams also cannot be modelled as a uniform material with an equivalent mean density as such results overestimate the propagation speed of the laser-driven ionization wave.

Recent interests in foam simulations led to the development of two-scale models [1,2,3], where a simplified interaction model is computed on the microscale in addition to the conventional macroscale hydrodynamics. These models describe the laser-foam interaction in terms of volumetric heating and expansion of planar or cylindrical, wire-like foam microstructure. However, further analysis of laser absorption in sub-wavelength objects and detailed particle-in-cell simulations show that laser is absorbed mostly at the surface of the overcritical elements and that ablation plays an important role in the overall dynamics. For this reason, the previous two-scale models have difficulties in explaining some of the experimental results. We present a novel approach that combines self-similar expansion of cylindrical elements with a surface ablation by laser.

Microscale model

In our microscale model, each foam pore is divided into two regions. The central region is a cylinder of radius a, length l_c, mass m_{cyl}, density $\rho_{\text{cyl}} = m_{\text{cyl}}/(\pi a^2 l_c)$ and temperature T_{cyl}. The rest of the pore is uniformly filled by the plasma mass m_{pl} ablated from the cylinder. The setup of the microscale model is depicted in Figure 1. Differential equations for the state variables are acquired from the conservation of mass and energy in the pore.

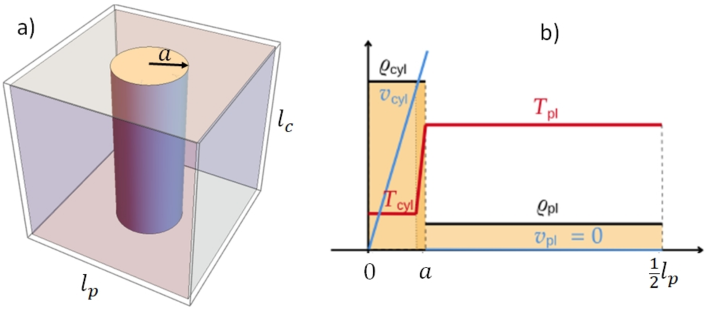

Figure 1: *The approximate pore in the hybrid model: a) the 3D view, b) the radial profiles.*

The incoming energy flux at the surface of the cylinder is divided into two parts related to ablation and heating

$$q_{\text{abl}} = (1-\zeta_{\text{las}})\frac{P_{\text{cyl}}}{2\pi a l_c} + (1-\zeta_{\text{th}})q_{\text{th}}, \qquad q_{\text{heat}} = \zeta_{\text{las}}\frac{P_{\text{cyl}}}{2\pi a l_c} + \zeta_{\text{th}} q_{\text{th}},$$

where q_{th} is the local heat flux from plasma (calculated as a fraction of the free-streaming limit) and P_{cyl} is the laser power absorbed in the cylinder. The absorption in the cylinder is based on the effective cross-section obtained from the Mie theory for electromagnetic scattering on cylindrical, sub-wavelength sized particles [4].

The radius of the cylinder changes due to the combined effect of expansion and ablation, while the cylinder mass decreases due to the ablation only

$$\dot{a} = v_{\text{exp}} - v_{\text{abl}}, \qquad \dot{m}_{\text{cyl}} = -\frac{2v_{\text{abl}}}{a} m_{\text{cyl}}.$$

The expansion velocity v_{exp} is calculated according to the model of self-similar isothermal expansion [5, 6] and the ablation velocity v_{abl} was taken from the stationary ablation model [7],

$$\dot{v}_{\text{exp}} = \frac{4}{3}\frac{\varepsilon_{\text{cyl}}}{a}\Theta(T_{\text{cyl}} - T_{\text{exp}}), \qquad v_{\text{abl}} = \min\left\{\frac{3}{8}\xi_a \frac{q_{\text{abl}}}{\rho_{\text{cyl}}(\varepsilon_{pe} + \varepsilon_{pi})}, \left(\frac{q_{\text{abl}}}{4\rho_{\text{cyl}}}\right)^{1/3}\right\}.$$

The model is finalized by the energy conservation relations for the specific internal energy of the cylinder ε_{cyl}, and the electron/ion internal energy ε_{pe}, ε_{pi} of the ambient plasma

$$\dot{\varepsilon}_{\text{cyl}} = \frac{2v_{\text{abl}}}{a}\left(\varepsilon_{\text{cyl}} + \frac{1}{4}v_{\text{exp}}^2\right) - \frac{2}{3}\frac{v_{\text{exp}}}{a}\varepsilon_{\text{cyl}}\Theta(T_{\text{cyl}} - T_{\text{exp}}) + \frac{2\pi a l_c}{m_{\text{cyl}}} q_{\text{heat}},$$

$$\dot{\varepsilon}_{pe} = -\frac{2v_{\mathrm{abl}}}{a}\frac{m_{\mathrm{cyl}}}{m_{\mathrm{pl}}}\varepsilon_{pe} + (1-\zeta_i)\frac{2\pi a l_c}{m_{\mathrm{pl}}}q_{\mathrm{abl}} + \frac{P_{\mathrm{ib}}}{m_{\mathrm{pl}}} - \frac{2\pi a l_c}{m_{\mathrm{pl}}}q_{\mathrm{th}} - W_{\mathrm{ei}} + W_e^{\mathrm{macro}},$$

$$\dot{\varepsilon}_{pi} = -\frac{2v_{\mathrm{abl}}}{a}\frac{m_{\mathrm{cyl}}}{m_{\mathrm{pl}}}\varepsilon_{pi} + \zeta_i\frac{2\pi a l_c}{m_{\mathrm{pl}}}q_{\mathrm{abl}} + W_{\mathrm{ei}} + W_i^{\mathrm{macro}}.$$

Here W_{ei} stands for the electron-ion temperature relaxation, $W_{e,i}^{\mathrm{macro}}$ are the energy fluxes from the neighbouring pores mediated by the macroscale heat conduction, and P_{ib} is the power deposited in plasma by inverse bremsstrahlung. Free parameters ζ_{las}, ζ_{th}, and ζ_i are introduced to control the energy repartition in the model, and ξ_a to control the ablation velocity.

Macroscale model

The hydrodynamic model on the macroscale comprises of the two-temperature Euler equations, supplemented by the electron/ion heat conductivity, electron-ion energy exchange, and laser source term. The laser propagation and deposition are described by a ray-tracing model and include a foam-induced scattering. The full set of Euler equations is solved in the part of the computational domain where all the foam pores have already been homogenised. For the non-homogenised foam cells/pores, a reduced set of macroscopic equations is assumed and the equations of the microscale model are solved using a 4th order Runge-Kutta method. Multiple micro-steps are performed for each hydrodynamic (macroscale) timestep. The pores are considered to be homogenised when the microscale densities reach the average density of the foam.

Results

Based on the settings of the free parameters of the model, three distinct regimes of operation were found from testing of the hybrid model in an isolated foam pore. These include:
(a) **Expansion dominated regime** ($\zeta_{\mathrm{las}} = 1$) for volumetric absorption of the laser in the cylinder, similar to previous sub-grid models [1, 2, 3], (b) **Combined ablation-expansion regime** ($\zeta_{\mathrm{las}} = 0$, $\zeta_{\mathrm{th}} = 0.5$) with the absorbed laser power converted to ablation and the heat flux divided equally between cylinder ablation and heating, (c) **Ablation dominated regime** ($\zeta_{\mathrm{las}} = 0$, $\zeta_{\mathrm{th}} = 10^{-2}$), where almost all energy deposited to cylinder is converted to ablation and only 1% is used on cylinder heating. The regimes differ significantly in the cylinder dynamics and the resulting homogenisation time of (c) is 5 times longer than for (a), with (b) being in between.

The sub-grid hybrid (ablation-expansion) model is implemented in the PALE and the FLASH hydrodynamic codes, and applied to simulate the recent experiments with foams at Shenguang III prototype laser, see [8] for more information about the setup. The preliminary results, shown in Figure 2, demonstrate that by varying the fraction of the energy flux used by ablation, one can efficiently control the laser propagation velocity and reduce it up to 3 times compared to the simulation with homogeneous target of equivalent density.

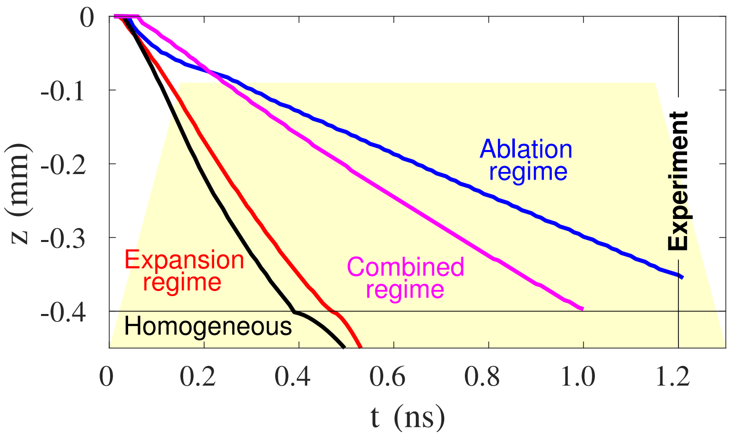

Figure 2: *The position of the ionisation wave front in the simulations of foam target (of thickness 400 μm and average density 10 mg/cm^3) with a laser beam of intensity 3.2 $\cdot 10^{14}$ W/cm^2 and wavelength* 351 *nm. Temporal shape of the laser pulse is shown as the yellow outline.*

Conclusions

In this paper, we have briefly presented a novel approach to the foam modeling that combines a self-similar expansion of cylindrical elements with a surface ablation by laser. The hybrid model has been applied to simulate the experiment at the Shenguang III prototype laser, and two of its regimes seem to produce results close to the experimentally observed propagation. Further comparison will include the plasma state parameters, in particular a ratio of electron-ion temperatures which depends on the details of homogenization process.

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