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An improved and fully implicit multi-group non-local electron transport model and its validations

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ABSTRACT

The combined effect of thermal flux inhibition and non-local electron heat flux in the radiation hydrodynamics (RHD) simulation of laser-driven systems can be accurately predicted by using non-local electron transport (NLET) models. These models can avoid commonly used space and time-independent *ad-hoc* flux-limiting procedures. However, the use of classical electron collision frequency in these models is rigorously valid for high temperature non-degenerate plasmas. In laser-driven systems, the electron thermal energy transport is important in regions between the critical density and ablation surface where the plasma is partially degenerate. Therefore, an improved model for electron collision frequency in this regime is required to accurately predict the thermal energy transport. Previously, we have reported an improved single group non-local electron transport model by using a wide-range electron collision frequency model valid from warm-dense matter (WDM) to fully ionized plasmas. In this work, we have extended this idea into a two-dimensional multi-group non-local electron transport (MG-NLET) model. Moreover, we have used a fully implicit numerical integration scheme in which the models for multi-group thermal radiation transport, laser absorption, electron-ion thermal energy relaxation and ion heat conduction are included in a single step. The performance of this improved MG-NLET model has been assessed by comparing the simulated foil trajectories with the reported experimental data for laser-driven plastic foils. The results indicate that the improved model yields results that are in better agreement with the experimental data.

1. Introduction

The interaction of an intense laser-beam with a solid target involves various complex phenomena [1] such as the absorption laser energy due to inverse-bremsstrahlung (IB) process in the expanding plasma below critical number density ($n_c \sim 1.1 \times 10^{27}/\lambda_\mu^2$ m^{-3}; where λ_μ is the laser wavelength in μm), non-linear electron heat conduction from the critical surface (where electron number density $n_e = n_c$) to the cold target, intense thermal radiation transport through optically thick solid target and optically thin low-density plasma and the generation of an intense shock-wave into the target. These physical processes are schematically shown in Fig. 1. Here, the non-linear electron thermal conduction (non-linearity is due $K_e \propto T_e^{5/2}$ [2], where K_e and T_e are the electron thermal conductivity and temperature, respectively) plays a critical role in the energy transport from the critical surface ($\mathcal{S}_c$) to the ablation surface ($\mathcal{S}_a$). For example, a reduction in the energy transport between $\mathcal{S}_c$ which lies in the expanded plasma region and $\mathcal{S}_a$ tends to decrease the drive efficiency. Moreover, it leads to a higher T_e in the expanded under-dense plasma and hence to a lower IB laser-energy absorption $\propto T_e^{-3/2}$. Therefore, the electron thermal conduction has a significant effect on the overall laser energy absorption. It also effects the ablation pressure, ablation velocity, length of the conduction zone, mass ablation rate, etc. Therefore, an accurate model for non-linear electron heat transport is critical in radiation-hydrodynamics (RHD) simulations of intense laser-driven systems.

The classical electron thermal conduction model of Spitzer and Harm [2] is governed by the divergence of electron heat-flux, $\nabla \cdot q_e = \nabla \cdot q_{SH}$; where, $q_{SH} = K_e \nabla T_e$ is the Spitzer–Harm (SH) heat-flux. The SH model assumes $\lambda_e << L_{T_e} = T_e/|\nabla T_e|$ such that the diffusion approximation (local gradient) for q_{SH} is valid. Here, λ_e and L_{T_e} are the electron collision mean free path and temperature scale length, respectively. However, in intense laser produced plasmas this approximation fails due to higher λ_e and short scale lengths due to high T_e and its steep gradients [3]. In the hotter region of the heat front, it is observed that $q_e << q_{SH}$ [4–6]. This is referred as thermal flux inhibition. On the other hand, at the base of the heat front $q_e > q_{SH}$. This is due to nearly collision-less hot electrons that are streaming away from the top of the heat front [5,6]. This transport is referred as *non-local* electron energy transport.

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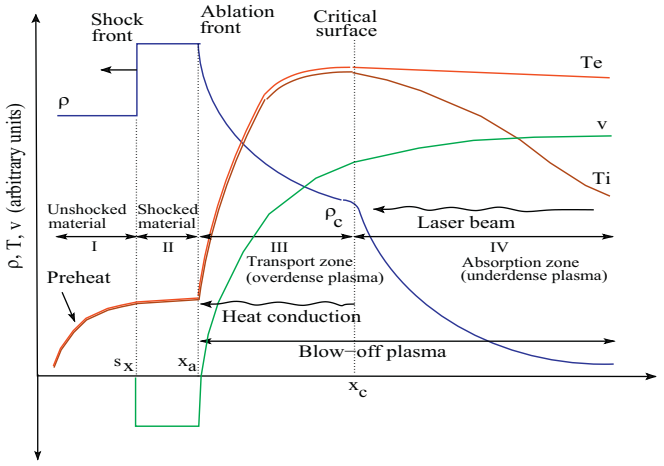

Fig. 1. Schematic of a laser-driven ablation in solids. The terms T_i and T_e are the ion and electron temperature, respectively. The material velocity and density are denoted as v and ρ, respectively. An over-dense (electron number density, $n_e > n_c$) plasma layer governed mainly by non-linear electron heat conduction forms between the critical surface and the ablation front.

In general, the effect of electron thermal flux inhibition in RHD simulations is accounted by limiting the electron heat flux q_e to a fraction $f \sim 0.7$ [4] of the *free-streaming* value $q_{FS} = n_e k T_e v_{th}$, where $v_{th} = \sqrt{kT_e/m_e}$, n_e, k and m_e are the electron thermal velocity, electron number density, Boltzmann constant and electron mass, respectively. This can be numerically achieved by modifying the heat flux as $q_e = \min(fq_{FS}, q_{SH})$ [4], or the thermal conductivity as $K = K_e q_f/(q_f + K_e|\nabla T_e|)$ [7]. This *ad hoc* flux limiting is relatively easy to implement in RHD codes. However, the value of flux-limiter f mostly need to be adjusted so as to match the experimental results. Therefore, the reported values of f in the literature varies from $0.001 - 0.7$ [7–17], that is from a strong to weak thermal flux inhibition. Moreover, it does not correctly account the effect of non-local electron energy transport.

The combined effect of aforementioned electron thermal flux inhibition and non-local transport in laser produced plasmas have been examined both numerically and/or experimentally by various authors [4–6,16–37]. Majority of the simulation models among these are based on the analytical or numerical solution of Fokker–Planck (FP) equations. In Ref. [38], Fokker–Planck calculation combined with one-dimensional hydrocode is used to study non-local electron thermal conduction and its effects on target implosions. The FP calculations are found to be accurate and are able to reproduce experimental results. However, FP simulations are computationally expensive and have difficulties to handle low T_e and high n_e regimes [39]. Therefore, the direct use of FP based models in multi-dimensional HD codes is cumbersome. Non-local electron transport models based on macroscopic fluid parameters are also reported to handle the thermal flux inhibition and non-local electron transport in HD simulations, see Refs. [5,6,18–21]. Most of these models are, however, one-dimensional (1D) in nature. Some multi-dimensional non-local electron transport models are also reported [30,40,41].

Majority of the reported non-local electron transport models use λ_e based on the classical electron collision frequency ν_e. However, the classical ν_e model is rigorously valid only for fully ionized and non-degenerate plasmas (low density and high T_e). In laser-driven systems, the energy transport due to thermal conduction is important in regions between the critical surface and the cold solid, where the plasma is partially degenerate. Therefore, in this regime, an improved λ_e or ν_e model in non-local electron transport models is desired to predict the electron energy transport more accurately.

Previously, in Ref. [42], we have improved the non-local electron transport model of Luciani et al. [5,6] by using a wide-range ν_e model [7,15,43,44] (hence λ_e) in place of classical ν_e (referred as LMV-I) . This wide-range ν_e model is valid from warm-dense matter (WDM) to fully ionized plasmas [42]. However, the LMV-I model is essentially a 1D model and the extension of LMV-I model into a MG model is computationally expensive as it involves the numerical integration of a convolution integral [5,6] for each electron energy group. Therefore, in the present work, we have followed an efficient, multi-dimensional, multi-group non-local electron transport (MG-NLET) model of Schurtz, Nicolai and Busquet [40,41] (SNB model) along with an improved model for λ_e [7,15,42–44] (referred as SNB-I).

A similar work can be found in Ref. [17], in which the original SNB model [40,41] has been improved by using a range formula [45] for λ_e. It is demonstrated in [17] that the use of range formula for λ_e in the SNB model [40,41] has significantly improved the results, especially in predicting pre-heats in cold targets. However, the range formula involves the integration of the equation for electron stopping power over a distance until the energy change is equal to the electron rest particle energy [17]. This distance has been taken as the improved electron mean free path for SNB calculations [17]. As there are multiple directions to integrate the electron stopping power equation [17], the direction pointing toward the center of the target (for spherical implosion) or in the direction of net shock-wave motion has been chosen in [17]. The improved ν_e (hence λ_e) model used in the present work, however, has the advantage that it depends only on the local macroscopic fluid variables.

It is worth mentioning here that the ab-initio based models/results for electron thermal conductivity and electron-ion collision frequency in WDM regime are reported recently [46–49]. These ab-initio results might be a better choice for improving the electron-ion collision frequency and electron thermal conductivity in the WDM regime. In the present work, however, we use ν_e model described in Refs. [7,15,43,44], which is relatively easy to implement using macroscopic fluid variables.

Other improvement made in this work is related to the numerical integration scheme of the governing equations and self-consistent coupling of the non-local model with other physical processes. In RHD simulations it is necessary to self-consistently couple the non-local electron transport model with various other relevant physical processes, such as hydrodynamics, multi-group thermal radiation, electron-ion energy relaxation, ion thermal conduction and laser energy absorption. In addition to that, a numerically stable integration scheme is essential for solving the governing equations. In Refs. [40,41], the governing multi-group SNB equations are solved by using a semi-explicit scheme in which the electron thermal conduction and the non-local electron transport are considered in a single step. An improved and efficient integration scheme of the coupled electron thermal conduction and the MG-SNB diffusion equations is also reported in Ref. [17]. This is achieved by using an operator split implicit scheme along with a predictor-corrector (PC) based iteration scheme to couple the electron thermal conduction and MG-NLET calculations. In the present work, in addition to the use of an improved λ_e in the SNB model, we have further improved the numerical integration scheme into a fully implicit and self-consistently coupled scheme in which all the above mentioned relevant physical processes (except HD) in RHD are included in a single implicit step. This numerical scheme, however, demands the storage of full sparse matrix elements and slightly higher overall computational time when all the relevant physical processes are included in the simulation. Despite these increased computational requirements, unlike an operator split scheme, it does not leave out any interesting physics and therefore it is self-consistent. Moreover, due to an implicit scheme the calculations are found to be stable.

The remainder of the paper is organized as follows: In Section 2, we have described the two-dimensional radiation hydrodynamics (2D-RHD) model and the governing equations. The equation-of-state (EOS) models used in the simulations are also briefly described