Numerical Analysis for Evaluation of Thermal and Optical Properties in Warm Dense Matter Generated by Pulsed Power Discharge

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ABSTRACT

Both numerical and experimental approaches are applied to evaluation for warm dense matter. To clear thermal and optical properties of warm dense matter, the numerical simulation of time-dependent one-dimensional thermal diffusion with radiative transfer is carried out in a compact pulsed power discharge device. The numerical model is described to include multi-group approximation for the radiation energy density distribution. Using the numerical model, the radiation energy density depended on the frequency is indicated with the experimental condition.

Keywords

Numerical Simulation, Pulsed Power Discharge, Warm Dense Matter, Thermal Diffusion, Radiation Energy Density, Absorption Coefficient, Multi-Group Approximation

1 Introduction

Property data of warm dense matter (WDM), which is in a transition regime from a solid to plasma, are important to control implosion dynamics in a fuel pellet of inertial confinement fusion (ICF) [1]. Because, to irradiate an energy driver such as intense lasers, high power X-ray, and high-current heavy ion beams, the material phase of the fuel pellet changes from solid to plasma conditions.

Since the WDM regime is in an extreme high pressure situation, it is difficult to create stationary the condition with a measurable setup. Consequently, the properties in the WDM regime are unclear.

Pulsed power discharge devices were used to generate the extreme state of matter from a solid to plasma [2–4]. For the generation of WDM with a well-defined condition, the apparatus with isochoric heating using a sapphire hollow capillary as a rigid body wall was proposed by using a table-top pulsed-power device [5]. In the experimental apparatus, the emission from the heated sample was observable due to the transparent sapphire capillary.

In our previous studies [6–8], we numerically investigate to generate the WDM by using pulsed power discharge devices to obtain the properties of the WDM. In this study, the numerical model with the thermodynamics and the radiation energy density is developed to obtain the thermal and optical properties of the WDM.

2 Numerical Modeling

In this study, we solve simultaneously the thermal diffusion and radiative transfer, and the details of the numerical model used in this paper were explained in Ref. [7]. Time-dependent one-dimensional thermal diffusion equation with cylindrical symmetry configuration is numerically solved to simulate the WDM generation in the compact pulsed power discharge experiment [5].

In the experimental setup [5], we can assume to calculate the phenomena in the foam/plasma ignoring the hydrodynamics, because the fluid dynamics of the sample plasma is limited by the capillary. For this reason, we only calculate the thermodynamics in the foam/plasma without the fluid dynamics of plasma. In the apparatus, a foamed copper is used as a sample, and is surrounded with a hollow sapphire capillary. The computational box used in this paper is adjusted in the experimental setup [6–8]. The inner region ($0 < r < 2.5$ mm) is the foamed copper as a sample, and the outer region (2.5 mm $< r <$ 4 mm) is the sapphire as a rigid capillary. The capillary length $L_{\rm cap}$ is 10 mm.

The density of the foamed copper surrounded in the hollow capillary is 0.1 times the solid density (8920 kg/m^3). The mass density of the sapphire is 3970 kg/m^3 as the solid. Since the sample is a foamed material, we assumed that the skin effect can be ignored. As a result, the discharge current distribution is assumed as uniform in the copper region.

The initial temperature is set as 300 K by a room temperature in the whole computational region. The conventional thermal property data of copper in solid, liquid, and gas phases are given by Refs. [9–12]. In the sapphire region, the material parameters for numerical simulation are 42 W/m-K for the thermal conductivity and 750 J/kg-K for the specific heat, as room temperature values.

The radiative transfer equation is solved by the diffusion approximation [13]. Although, the WDM regime is expected to be quite thick optically, the radiation generated in the interior of the WDM region is not able to pass through the WDM region. For this reason, the diffusion equation for the radiation energy density E^g is modified by

$$\frac{\partial E^g}{\partial t} = (4\pi B^g - c\,E^g)\,\kappa_{\rm P}^g, \qquad (1)$$

along the radius r in the cylindrical coordinate with a multi-group approximation in the frequency domain group g [14]. Here, E^g is the radiation energy density at g th group,

$$E^g = \frac{\int_{\nu_g}^{\nu_{g+1}} E_\nu \, d\nu}{\int_{\nu_g}^{\nu_{g+1}} d\nu}, \qquad (2)$$

and

$$\kappa_{\rm P}{}^g = \frac{\int_{\nu_g}^{\nu_{g+1}} \kappa_\nu \, B_\nu \, d\nu}{\int_{\nu_g}^{\nu_{g+1}} B_\nu \, d\nu}, \qquad (3)$$

is the Planck absorption coefficient at g th group [15], $k_{\rm B}$ is the Boltzmann constant, and the blackbody intensity is

$$B^g = \frac{\int_{\nu_g}^{\nu_{g+1}} B_\nu \, d\nu}{\int_{\nu_g}^{\nu_{g+1}} d\nu}. \qquad (4)$$

According to the measuring instrument in the experimental setup [16], the frequency domain is divided and grouped as the following Table 1.

Table 1: Relation between group number and frequency domain for multi-group approximation of radiation energy density. Here, the wavelength λ of radiation is defined by the speed of light c / the frequency ν.

Group g	Wavelength λ
1	$>$ 800 nm
2	800 $\sim$ 680 nm
3	680 $\sim$ 520 nm
4	520 $\sim$ 370 nm
5	370 $\sim$ 340 nm
6	$<$ 340 nm

The κ_ν [1/cm] is the frequency ν dependent absorption coefficient [17],

$$\kappa_\nu = 7.13 \times 10^{-16} \frac{n_{\rm i}(Z^* + 1)^2 \exp\{-(\xi - \chi)\}}{T^2 \chi^3}, \qquad (5)$$

where $n_{\rm i}$ is the ionic density [1/cm^3], Z^* is the mean ionization degree (0.5 is assumed from the previous experimental result [5]), $\chi = h\nu/T$, and $\xi = I_0/T$. h is the Planck constant, I_0 is the mean ionization potential (7.73 eV for Cu), and T is the temperature with unit [eV] in this equation.

The radiative transfer with the flux limited diffusion approximation [18] is calculated by [7]

$$\frac{\partial E^g}{\partial t} = -\frac{c}{r}\frac{\partial E^g}{\partial r}, \qquad (6)$$

in the sapphire region.

The input power history is given by the corresponding experimental data [5, 16].

3 Calculation Result

The numerical simulation confirmed that the sample was achieved to be the temperature generating WDM [6, 7], and the result could be compared with the experimental result [5]. The result indicated that the temperature at the interface between the copper foam and the sapphire capillary was diffused, and the temperature around the edge of copper region is reduced due to the difference of the heat capacities [7,8]. The numerical result with one-group approximation for the radiation transfer was compared with the experimental result [16].

Figure 1 shows the radiation energy density distributions as a function of time at each frequency group given by the numerical simulation of time-dependent phenomena in the copper foam and the sapphire capillary regions. The radiation energy density distribution at each frequency group corresponds to the temperature distribution [7].

Figure 2 shows the numerically obtained radiation energy density observed at edge of capillary ($r = 4$ mm) as a function of time at each frequency group. The previous experiment indicated that the sample temperature achieved to be around 5000 K [5]. From Wien displacement law [19], the wavelength of the maximum black-body emission, which is given by $\lambda_W = 2.5 \times 10^{-7}/(T[\mathrm{eV}])$, is estimated at 580 nm for 5000 K. In this calculation, the wavelength of 580 nm is included in the domain at $g = 3$, and the calculation result in Fig. 2 is confirmed with the experimental result.

When the emission intensity measurement with the multi-channel spectroscopy system [16] is completed, the radiative transfer calculation can be confirmed with the experimental results, and the calculation result will support the experimental results through the radiation distribution.

4 Conclusion

In this study, it was considered that both the numerical and experimental approaches were applied to evaluation for WDM. To clear the thermal and optical properties of WDM, the numerical simulation of time-dependent one-dimensional thermal diffusion with radiative transfer was carried out in the compact pulsed-power discharge device. The numerical model was described to include the multi-group approximation for the radiation energy density. Using the numerical model, the radiation energy density depended on the frequency was shown with the experimental condition.

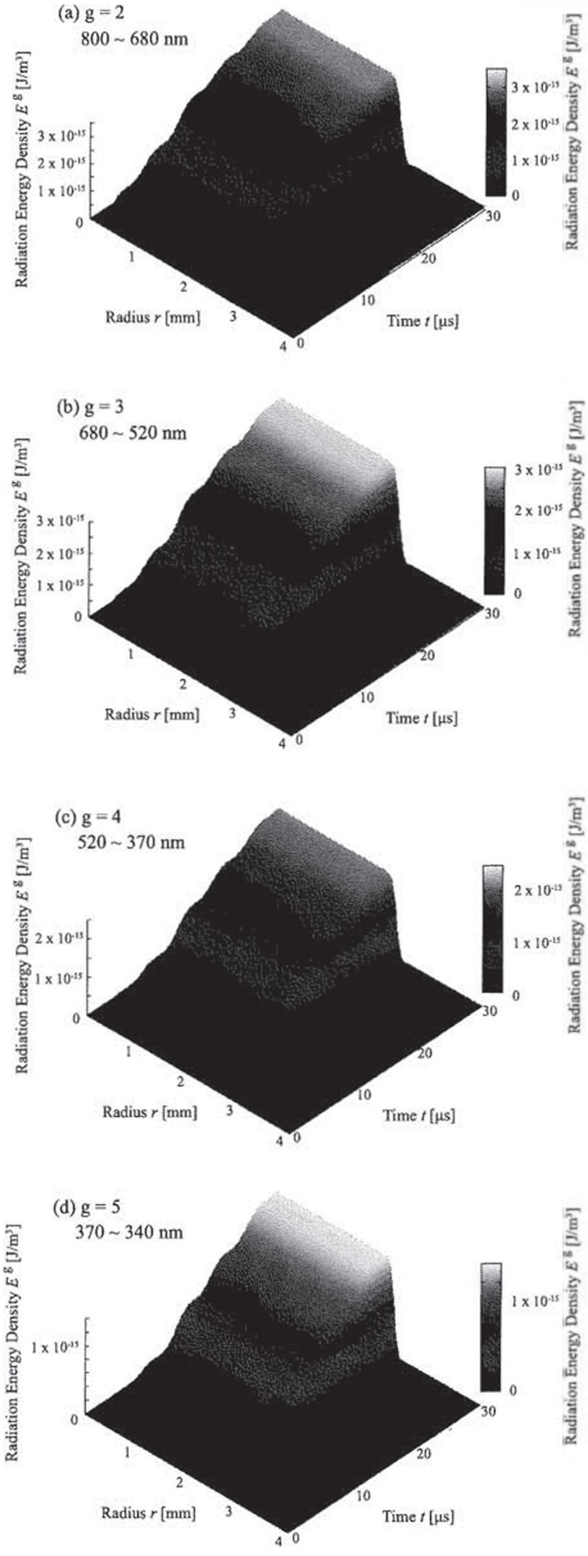

Figure 1: Radiation energy density distributions as a function of time at each frequency domain grouped, (a) for $g = 2$, (b) for $g = 3$, (c) for $g = 4$, and (d) for $g = 5$, respectively.

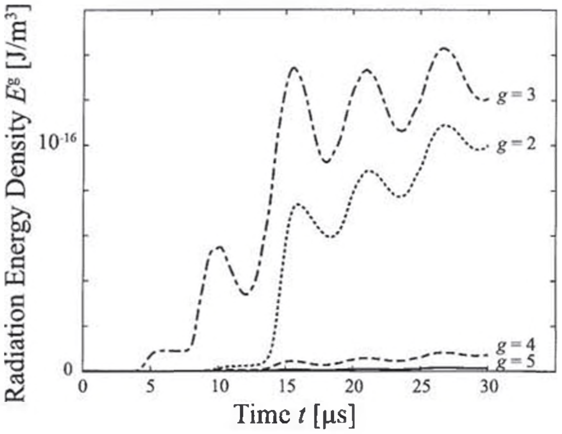

Figure 2: Radiation energy density observed at edge of capillary ($r = 4$ mm) as a function of time at each frequency grouped. The dotted line indicates the radiation energy density for $g = 2$, the dashed-dotted curve indicates the radiation energy density for $g = 3$, the dashed line shows the radiation energy density for $g = 4$, and the solid curve shows the radiation energy density for $g = 5$, respectively.

For the evaluation of the optical and thermal properties in the WDM regime, the numerical model developed will be applied in the various experimental conditions, and the calculation results will be confirmed with the experimental results in our near future work.

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