Numerical Simulation on Measurement of Optical and Thermal Properties for Warm Dense Matter Generated by Isochoric Heating with Pulsed Power Discharge Device

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Abstract. Property data in warm dense matter (WDM) are important to optimize implosion dynamics in a fuel pellet of inertial confinement fusion (ICF). A table-top pulsed power discharge device with isochoric heating using a sapphire hollow capillary was proposed, and was used to generate the extreme state of matter with a well-defined condition. We investigated numerically to generate the WDM by using the pulsed power discharge device. The numerical model was developed by time-dependent one-dimensional thermal diffusion with radiative transfer of multi-group approximation, and the numerical simulation was carried out according with the experimental condition. The achieved temperature of the numerical simulation result was confirmed by the previous experimental result. Also, the radiation energy density was shown at each group of the wavelength of emission.

1. Introduction
Warm dense matter (WDM) is in a transition regime from a solid to plasma, and the property data 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. 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 [2, 3]. In the experimental apparatus, the emission from the heated sample was observable due to the transparent sapphire capillary.

In our previous studies [4, 5, 6, 7], we numerically investigated to generate the WDM by using pulsed power discharge devices to obtain the properties of the WDM. In this study, the
Figure 1. Experimental setup in WDM generation for isochoric heating with pulsed power discharge and calculation region.

A numerical model with the thermodynamics and the radiation transfer is developed, and the calculation is demonstrated to obtain the thermal and optical properties of the WDM.

2. Numerical model

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 [2, 3]. The details of the numerical model used in this paper were explained in Ref. [5].

In the experimental setup [2, 3], 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. Figure 1 shows the experimental setup in the WDM generation for the isochoric heating with the pulsed power discharge and the calculation region in this study. In the apparatus, a foamed copper is used as a sample, and is surrounded with a hollow sapphire capillary. The computational box is adjusted in the experimental setup [4, 5, 6, 7]. 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 is 10 mm.

The density of the foamed copper is 0.1 times the solid density (8020 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. [8, 9, 10]. 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 [11]. The diffusion equation for the radiation energy density $E^g$ is given by

$$ \frac{\partial E^g}{\partial t} - \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{c}{3 \kappa_R} \frac{\partial E^g}{\partial r} \right) = (4\pi B^g - cE^g) \kappa_P^g, \tag{1} $$

along the radius $r$ in the cylindrical coordinate with a multi-group approximation in the frequency domain group $g$ [1]. Here, $\kappa_R^g$ and $\kappa_P^g$ are the Rosseland and the Planck absorption coefficients at $g$ th group [12], and $B^g$ is the blackbody intensity.
Table 1. Relation between group number and frequency domain for multi-group approximation. Here, the wavelength $\lambda$ of radiation is defined by the speed of light $c$ / the frequency $\nu$.

| Group $g$ | Wavelength $\lambda$ |
|-----------|-------------------|
| 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        |

Figure 2. Temperature of sample during pulsed power discharge.

Figure 3. Radiation energy density at outer edge at each group.

According to the measuring instrument in the experimental setup [13], the frequency domain is divided and grouped as Table 1.

The $\kappa_\nu(\rho, T, Z^*, \nu)$ is the frequency $\nu$ dependent absorption coefficient [14], where $\rho$, $T$, and $Z^*$ are the density, the temperature, and the mean ionization degree (0.5 is assumed from the previous experimental result [2, 3]), respectively.

The radiative transfer with the flux limited diffusion approximation [15] is calculated by [5]

$$\frac{\partial E^g}{\partial t} = -c \frac{\partial E^g}{r \partial r},$$

(2)

in the sapphire region. Eqs. (1) and (2) are solved numerically by the implicit method.

The input power history is given by the corresponding experimental data [2, 13].

3. Simulation result

Figure 2 shows the temperature of the sample during the pulsed power discharge. The previous experimental result indicated that the sample temperature increased up to 5000 K at around 10 $\mu$s [2]. The calculation result shows that the temperature of the interior of the sample achieved to 5000 K at 10 $\mu$s. As a result, the calculation result corresponds to the previous experimental result until 10 $\mu$s.

However, the temperature for the calculation result indicated to be achieved over 7000 K after 10 $\mu$s. It is implied that the disagreement between the experimental and numerical results was caused due to lack of accurate thermodynamic property data, because of the boiling point for Cu is about 6000 K.
Figures 3 and 4 show the radiation energy density distributions at outer edge and in the entire of the calculation region at each group. Due to the measurement system [13], it is expected that the emission intensity from the WDM is observed experimentally such as shown in Fig. 3. Since the WDM is in the optically thick, the radiation energy density is uniform distribution at each group in the sample region except around the interface between the sample and the sapphire capillary.

In comparison with the experimental and numerical results in one-group approximation, the observed emission intensity corresponded qualitatively to the calculated radiation energy density [13]. When the fast multi-group analyzing spectrocope by ellipsometry observes experimentally the emission intensity from the generated WDM, the numerical results as shown in Fig. 3 are compared to the experimental results.

4. Conclusion
To obtain the property data of WDM, both the experimental and numerical approaches were proposed. In this study, the numerical modeling and the numerical simulation were carried out according with the experimental setup by the pulsed power discharge device with isochoric heating. The achieved temperature of the numerical simulation result was confirmed by the previous experimental result. Consequently, the numerical simulation was useful to understand the thermodynamic properties during the discharge in comparison with the experimental results. To improve the opacity model and so on, the radiative transfer calculation will be quantitatively confirmed with the experimental results.

Acknowledgments
This work was supported from MEXT Grant-in-Aid for Scientific Research, and by Program for High Reliable Materials Design and Manufacturing in Nagaoka University of Technology, and by JSPS Grant-in-Aid for Challenging Exploratory Research No.25630418.

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