Two-Dimensional Simulation of a Plume Produced by Ablation in the Liquid Wall Chamber of KOYO-Fast

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(Received 12 September 2015 / Accepted 6 April 2016)

An integrated two-dimensional ablation simulation code DECORE-2D (DEsign COde for REactor) has been developed to estimate the environment of the liquid wall chamber of KOYO-fast. Density profiles of ablated lead are estimated using DECORE-2D for the case of first ignition with 200 MJ fusion power output. To discuss the stagnation of ablated materials in the chamber, the divergence of ablated material with phase change was analyzed in two-dimensional planar geometry. The spread angle of a plume obtained by this simulation is roughly 1°. This result indicates that the stagnation of ablated materials can be discussed with straight flows from tiles tilted by 30° to the tangential direction.

Keywords: simulation, environment in chamber, liquid wall, plume, ablation, KOYO-fast

DOI: 10.1585/pfr.11.1405084

1. Introduction

A design of a laser fusion reactor with a liquid wall, KOYO-fast, is reported in Refs. [1–3]. Figure 1 shows the simple outline of the first wall of KOYO-fast. KOYO-fast is the conceptual design of a commercial laser fusion reactor based on a fast ignition scheme. Its electric output power is 1.28 GW, and it has four modular chambers that are driven with a 16 Hz, 1.2 MJ/pulse laser. The chamber has a cascade-type first wall that has a serrated configuration in the horizontal cross section as shown in Fig. 2. The size of "one fall" is 30 cm in height, roughly 80 - 150 cm in width and 3 mm in thickness.

One of the critical issues of a laser fusion reactor with a liquid wall is chamber clearance [1–3]. After a micro explosion with a 200-MJ fusion power output, liquid metal ablates from the surface because of heating by α particles, ions and debris from the target. Plumes produced by ablation form mists and clusters owing to collisions between plumes near the center of the liquid wall chamber. To prevent such phenomena, the structure of the first wall of the chamber is made of components that similar to a tile, as shown in Fig. 2. The width of a tile of the first wall of KOYO-fast is roughly 80 cm at the chamber radius is 300 cm. The slope of a tile of the first wall of KOYO-fast is 30°.

An integrated two-dimensional ablation simulation code DECORE-2D (DEsign COde for REactor) has been developed to estimate the environment in the laser fusion

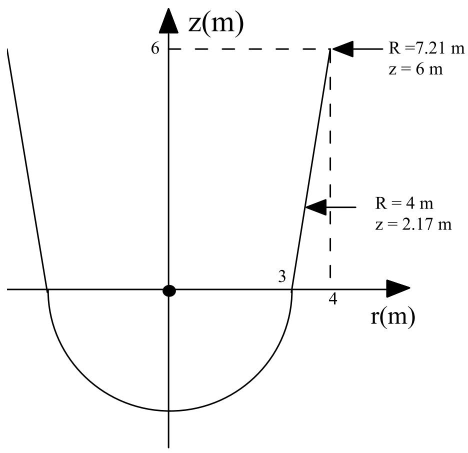

Fig. 1 The simple outline of the first wall of KOYO-fast.

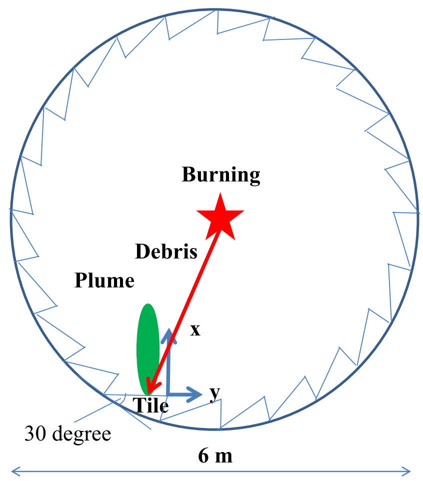

Fig. 2 The structure of the first wall of the chamber.

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liquid wall chamber of KOYO-fast [4–6]. Density profiles, temperature profiles, and the spread angle of ablated lead are estimated using DECORE-2D for the case of first ignition with 200 MJ fusion power output.

2. Two-Dimensional Simulation Models [4–6]

Pulse shapes of irradiated intensities of X-ray and charged particles on the surface of the liquid wall at a distance of 3 m from the target are shown in Fig. 3 [4,5]. Note that time (time = 0 in the figure) refers to the time the heating laser is irradiated on the target. At time = 2000 ns, the heat load is less than 100 W/str/cm^2. We assume that after time = 2000 ns, there is no heat load in our simulation.

Figure 4 is the schematic of the relation of a tile and the burning point in the chamber.

Figure 5 shows the geometry of the two-dimensional simulation model 1. We consider a zone 1 cm from the edge of a tile. X-rays, α particles, and debris particles uniformly irradiate the regime in the y-direction. The calculation area was from −0.3 cm to 10 cm in the x-direction and from −1 cm to 3 cm in the y-direction.

Figure 6 shows the geometry of two-dimensional simulation model 2. We consider zone 2 cm from the edge of a tile. The calculation area was from −0.3 cm to 10 cm in the x-direction and from −2 cm to 3 cm in the y-direction. The function of irradiation intensities of the X-rays, α particles, and debris particles are given as follows. (note that y is in cm, and $I_{300\,\mathrm{cm}}(t)$ is shown in Fig. 3).:

$$I(y,t) = I_{300\,\mathrm{cm}}(t)\, I(y),$$
$$I(y) = \frac{300^2}{(70-y)^2 + 3\times 150^2}\,\frac{150\sqrt{3}}{\sqrt{(70-y)^2 + 3\times 150^2}} \quad (1)$$

Figure 7 shows the y dependence of the irradiation intensities, $I(y)$ in Eq. (1). As shown in Fig. 7, the irradiated intensity on a tile decreases as y decreases. The main part that determines the spread angle of a plume in y-direction is that near $y = 0$.

The models dealing with stopping power in liquid lead, and high Z and low-temperature plasmas is described

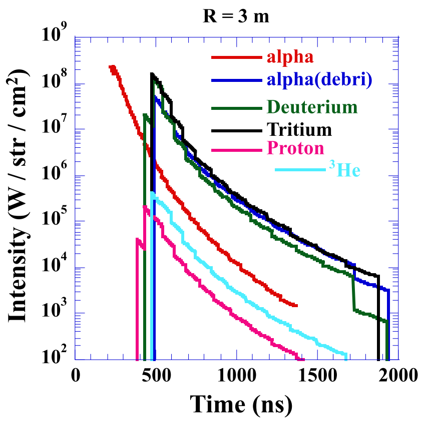

Fig. 3 Pulse shapes of irradiated charged particles on the surface of the liquid wall at a distance of 3 m from the target.

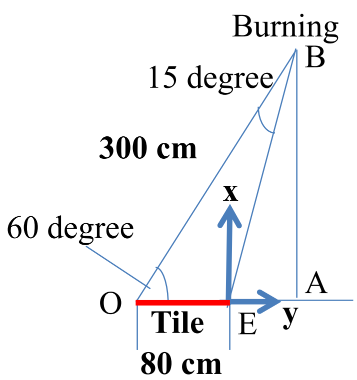

Fig. 4 The schematic of the relation of a tile and the burning point in the chamber.

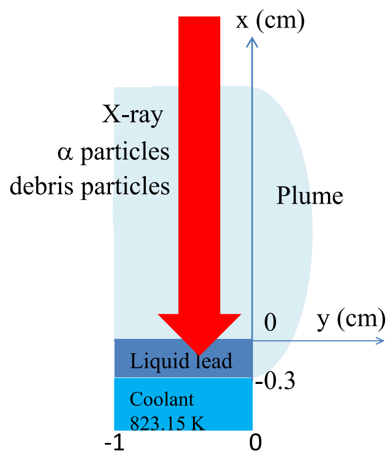

Fig. 5 Geometry of two-dimensional simulation model 1.

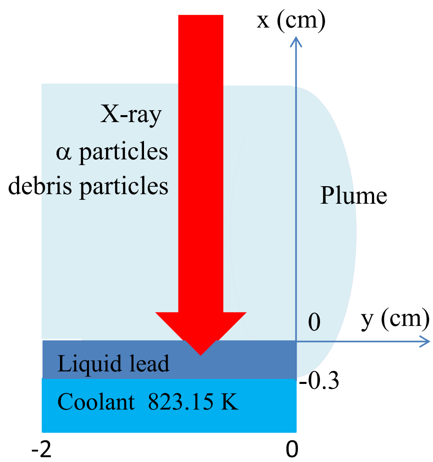

Fig. 6 Geometry of two-dimensional simulation model 2.

in Refs. [4] and [7], respectively.

Basic equations of a fluid motion are equation of continue, equation of motion, and equation of energy. We extend DECORE from the one-dimensional version to the two-dimensional version using CIP-CSL2 and M-type CIP [8].

We decided that the material of the liquid wall was liquid lead instead of lithium-lead for our simulations. In liquid lithium-lead, Li and Pb are uniformly distributed. Ablation occurs in a sufficiently short time. Therefore, we can ignore the effect of the latent heat of lithium. We can assume that the main part of motions of lithium-lead can be represented by lead.

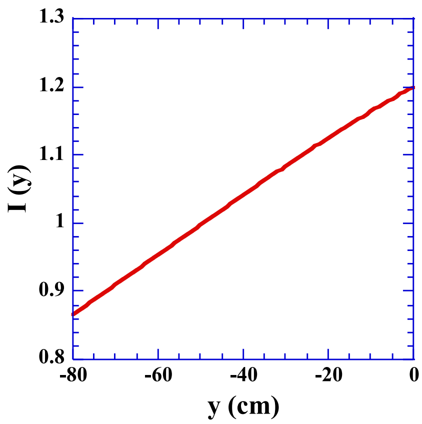

Fig. 7 y dependence of irradiated intensities, $I(y)$ in Eq. (1).

The initial temperature of liquid lead and the coolant temperature are 823.15 K according to the operating conditions of KOYO-fast [1–3]. The initial thickness of liquid lead is 0.3 cm because it was found that liquid-film flow could be stably established with thickness of 0.3 - 0.5 cm [9–11].

Note that the flow speed of liquid lead is sufficiently slow so that its vertical movement is negligible.

3. Results and Discussions

Figure 8 shows the particle-number density profiles obtained from simulation model 1. As shown in Fig. 8, tops of plumes at time = 0, 2, 5, and 8 μs are not spread in the y-direction.

Figure 9 shows temperature profiles obtained from simulation model 1. As shown in Fig. 9, the temperature of a plume at time = 8 μs is almost 823.15 K, which is the operating temperature of KOYO-fast. As shown in Fig. 9, an ablation plume enters a steady-state.

We estimate time evolutions of fluxes in the x-

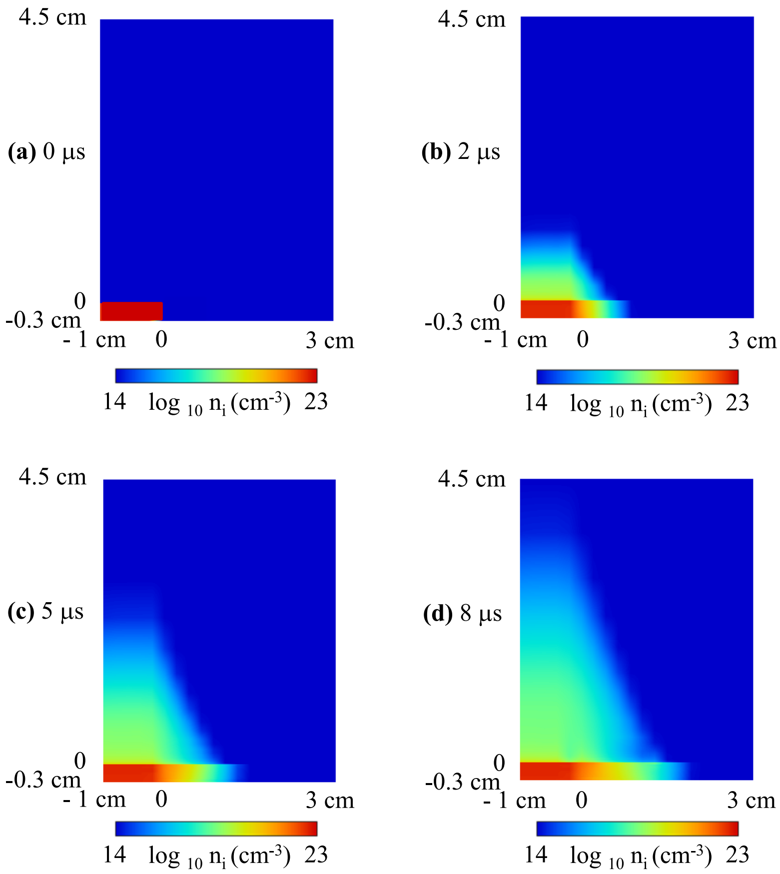

Fig. 8 Particle number density profiles obtained from simulation model 1. at (a) 0 μs, (b) 2 μs, (c) 5 μs, and (d) 8 μs.

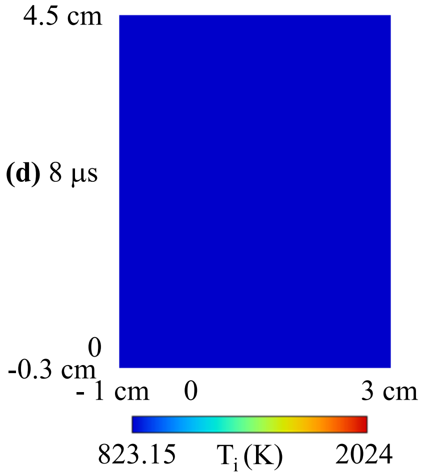

Fig. 9 Temperature profiles obtained from simulation model 1, at 8 µs.

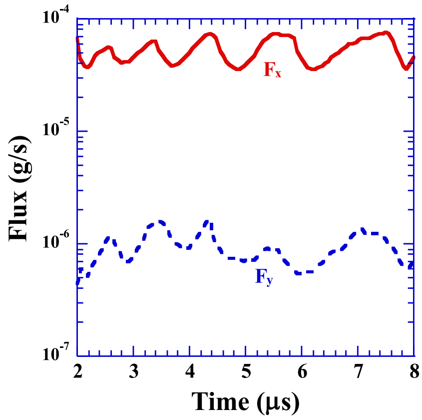

Fig. 10 Time evolutions of fluxes in the x-direction and y-direction.

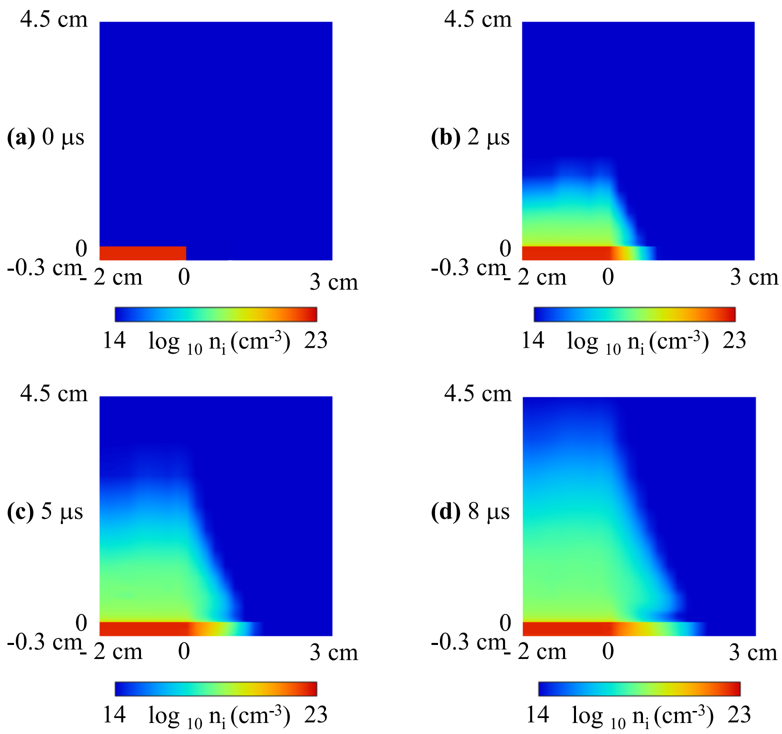

Fig. 11 Particle number density profiles obtained from simulation model 2. at (a) 0 µs, (b) 2 µs, (c) 5 µs, and (d) 8 µs.

direction and y-direction as follows;.

$$F_x(t) = \int_S \rho(x, y, t)\, v_x(x, y, t)\, \mathrm{d}s, \tag{2}$$

$$F_y(t) = \int_S \rho(x, y, t)\, v_y(x, y, t)\, \mathrm{d}s, \tag{3}$$

where ρ is mass density, v_x is velocity in x-direction, and v_y is velocity in y-direction. S is the boundary of a plume and vacuum in the simulation area. Figure 10 shows time evolutions of fluxes in the x-direction and y-direction obtained from simulation model 1.

We estimate that the time average of the ratio of F_y to F_x is roughly 0.02 in the simulation area.

We estimate the spread angle of a plume in the y-direction δ as follows;.

$$\delta = \tan^{-1}\left[\left\langle F_y(t)/F_x(t)\right\rangle\right] \approx \tan^{-1}(0.02)$$
$$= 0.02\,\mathrm{rad} \approx 1\ \mathrm{degree}, \tag{4}$$

where bracket notation donates a time averaged value. The spread angle of a plume is roughly 1° in the case of model 1.

Figure 11 shows particle number density profiles obtained from simulation model 2. As shown in Fig. 11, tops of plumes at time = 0, 2, 5, and 8 µs are not spread in the y-direction.

Figure 12 shows the temperature profiles obtained from simulation model 2. As shown in Fig. 12, an abla-

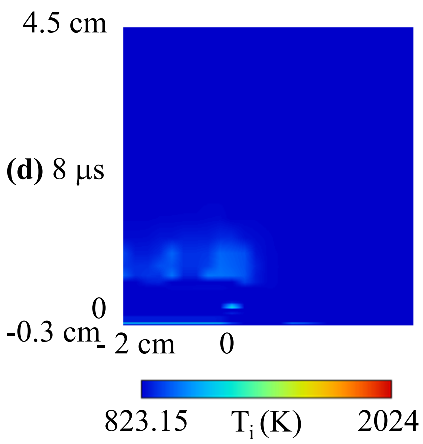

Fig. 12 Temperature profiles obtained by simulation model 2, (d) at 8 μs.

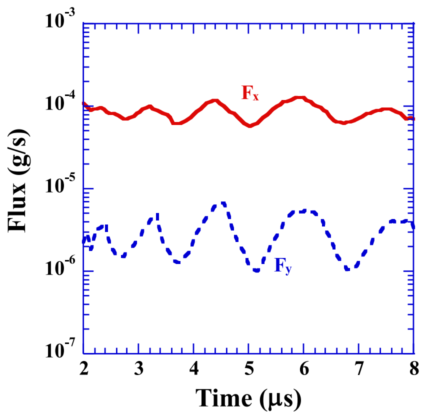

Fig. 13 Time evolutions of fluxes in the x-direction and y-direction.

tion plume enters a steady-state.

Figure 13 shows the time evolutions of fluxes in the x-direction and y-direction obtained from simulation model 2. We estimate that time average of the ratio of F_y to F_x is roughly 0.02 in the simulation area. We estimate the spread angle of a plume in the y-direction, δ, is roughly 1° in the case of model 2.

As shown in Fig. 7, in the previous section, the irradiated intensity on a tile decreases as y decreases. The main part that determines the spread angle of a plume in the y-direction is the section near $y = 0$. Therefore, these two simulation results are sufficient to lead to a generalized conclusion on the spread angle of a plume.

4. Concluding Remarks

An integrated two-dimensional ablation simulation code DECORE-2D (DEsign COde for REactor) has been developed to estimate the environment of the liquid wall chamber of KOYO-fast. Density profiles of ablated lead are estimated for the case of first ignition with a 200-MJ fusion power output. The width of a tile of the first wall of KOYO-fast is roughly 80 cm at the chamber radius is 300 cm. The slope of a tile of the first wall of KOYO-fast is 30°. We estimate that the spread angle of a plume is roughly 1°.

This result indicates that stagnation of ablated materials can be discussed assuming that the ablation plume from a tile is a simple straight flow. Analysis of interactions with neighbor plumes is targeted in a future study.

Acknowledgments

This work is performed with the support and under the auspices of the NIFS Collaborative Research Program. (NIFS14KUGK079)

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