Experimental Investigation of Aerosol Formation in Laser Fusion Reactor Chamber by Discharge Method

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Abstract. Liquid wall chambers are one of the most critical technologies in inertial fusion energy (IFE) plants. The critical problem for the liquid wall IFE chamber is the chamber clearance after laser shots. This paper presents preliminary results from an experimental simulation of ablation processes induced by alpha-particle heating.

1. Introduction

A liquid LiPb flow, whose flow rate is stabilized using a cascade scheme, is being considered for the first wall of the fast-ignition laser-fusion power plant, KOYO-Fast. The first wall is irradiated by pulses of X-rays, neutrons, and charged particles generated by fusion burning [1]. The heating effect of alpha particles needs to be considered, especially when determining the ablation of the first surface, since alpha particles deposit their energy in a short range of about 10 μm [2]. Alpha particles release their energy when they are completely stopped inside the liquid wall. The energy density of alpha particles at the surface is estimated to be 0.35 MJ/m². Ablation of the liquid wall occurs because the temperature inside the wall becomes higher than that at its surface. It resembles a 10-μm-thick membrane peeling off from its surface. In the case of KOYO-F, 10 kg of LiPb evaporates after each laser shot [3]. In this experiment, we aimed to simulate the formation and distribution of aerosols from a plane source and also the hydrodynamic phenomena. Some pioneering studies on the formation and behaviour of aerosols are described in Ref. [4]. In previous studies, formation of aerosols was discussed in terms of laser heating and only surface heating by thermal conduction. In this present study, we used a discharge method to simulate volumetric heating.

2. Experimental methods

2.1. Discharge method

A monolayer film was used to investigate the spatial distribution of aerosols from a plane source. In addition, a multilayer film consisting of layers having different thermal conductivities was used to investigate formation of aerosols in the presence of hydrodynamic instabilities. For simplicity, the influence of Li was ignored in this experiment. A Pb membrane was evaporated and, after expansion and thermal radiation cooling, the Pb vapour in the slow component formed aerosols. A schematic diagram of the experimental set up is shown in Fig. 1. The specifications of the discharge circuit used in this experiment were: a capacitor of C=150 μF, an applied voltage of V=1 kV, a Pb membrane having dimensions 5.0 mm×10.0 mm×12.2 μm. The available energy stored in the capacitor was 75 J.
The discharge current was monitored using the potential drop between the ignitron and the capacitor and a high-voltage probe was connected across the anode and cathode electrodes to detect the discharge voltage.

![Schematic diagram of the discharge circuit and plasma monitoring system.](image)

**Figure 1.** Schematic diagram of the discharge circuit and plasma monitoring system.

### 2.2. Temperature measurement

The Pb membrane was converted from a solid to a plasma by pulse heating. Plasma emission was detected using a charge-coupled device (CCD) camera equipped with bandpass filters which were inserted in front of two of the pinholes to disperse the plasma emission at 460 nm and 660 nm in order to determine the colour temperature. An amplified photodetector was used to measure the temporal variation of the emission. The following relational expression for the colour temperature was used [5],

\[
\frac{r_{\text{plasma}}(\lambda_B) \cdot r_{\text{halogen}}(\lambda_R)}{S_b(\lambda_B, T_{D,\text{plasma}}) \cdot S_b(\lambda_R, T_{D,\text{halogen}})} = \frac{S_b(\lambda_B, T_{D,\text{plasma}}) \cdot S_b(\lambda_R, T_{D,\text{halogen}})}{S_b(\lambda_B, T_{D,\text{plasma}}) \cdot S_b(\lambda_R, T_{D,\text{halogen}})}
\]

(1)

\(S_b(\lambda, T_p)\) is the relative spectral distribution, which is subjected to the Planck radiation law and is given as follows:

\[
S_b(\lambda, T_p) = \frac{C \lambda^5 \exp\left(\frac{c_2}{\lambda T_p}\right) - 1}{\lambda^5 \exp\left(\frac{c_2}{\lambda T_p}\right) - 1}
\]

(2)

where \(\lambda_B\) and \(\lambda_R\) are 460 nm and 660 nm, respectively. \(r_{\text{halogen}}(\lambda)\) and \(r_{\text{plasma}}(\lambda)\) are the response of the standard halogen lamp, the colour temperature of which was 3000 K and the plasma emission, respectively. \(c_2\) is the second emission coefficient, \(C\) is an arbitrary constant and \(T_D\) is the temperature. In this experiment, we calculated the colour temperature of Pb plasma emission at 460 nm and 660 nm with limited influence of Pb atomic emission [6].

### 2.3. Capture of Aerosols

The slow components of the ablated vapour form aerosols due to condensation of the Pb vapour. We measured the particle size and distribution of these aerosols. The distances between the Pb membrane and the glass used to capture the aerosols were \(L=5, 10, 12, 20\) mm. The internal pressure in the experimental chamber was \(P=12.5\) Pa.
3. Experimental results

3.1. Heating power and emission from plasmas
The goal of this analysis was to determine the heating rate and the temperature of the vapour source. We simultaneously detected the pulse current, discharge voltage and intensity of visible light after discharge. The discharge power and energy of the Pb membrane are plotted as a function of time in Fig. 2.

\[ P = VI \quad \text{and} \quad E = \int P \, dt \]

where, \( V \) is the discharge voltage and \( I \) is the pulse current. The current pattern was a dumping oscillation due to the low resistance of the discharge circuit. The discharge power has two large peaks. 10% of the energy stored in the condenser was expended heating the Pb membrane. To calibrate the colour temperature measurement, we measured the CCD response to 10-ms exposure to the standard halogen lamp and to plasma emission. The average plasma was determined using this calibration data and Eqn. (1), and found to be \( T_{\text{pl}} = 4050 \pm 53 \, \text{K} \).

3.2. Captured aerosols
Figure 3-(a) shows an AFM image (Atomic Force Microscope) of the aerosols deposited on the glass plate and figure 3-(b) shows a SEM image (Scanning Electron Microscope) of a cross sectional view of captured aerosols that were deposited at 20 mm front of the ablation source and the chamber pressure at discharge was 12.5 Pa. The diameters of the clusters of aerosol particles ranged from 20 to 40 nm and spherical particles are deposited on a continuous membrane. Figure 3-(b) indicates that leading hot vapour was captured as the membrane and trailing slow components, which were cooled-aerosols, were deposited as the particles. Table 1 shows the experimental results for diameter of captured aerosol particles and average mass of deposited aerosols. The areal mass density was determined by the intensity of X-ray-stimulated fluorescence. When L is shorter, the diameter is larger. This indicates that either particles are grown-up larger in the stagnated vapour between the source and the capture plate or particles are grown-up on the capture plate.
Figure 3. AFM (a) and SEM (b) photograph of the deposited aerosols from the Pb membrane.

Table 1. Comparative chart of the deposited particles.

| Deposition distance (mm) | Diameter of particle (nm) | Average areal mass density (g/m²) |
|-------------------------|---------------------------|----------------------------------|
| 5                       | 100-200                   | 0.93                             |
| 10                      | 50-150                    | 0.78                             |
| 20                      | 20-40                     | 0.40                             |

4. Summary

A monolayer membrane was used to compare the results of a numerical simulation of aerosol formation with experimental results. Preliminary results indicate that growth of aerosols strongly depends on the geometrical effect formed by the source plate and capture plate. Further investigations are necessary to determine whether captured particles are grown in flight or on the capture plate.

References

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