Simulation on Plume Formation and Study on Environment in Laser Fusion Liquid Wall Reactor Chamber

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One of the critical issue of a laser fusion reactor with a liquid wall is the chamber clearance. After micro explosion with 200 MJ nuclear yield, about 10 kg of liquid metal evaporates from the surface due to heating by particles, ions and debris from the target. The evaporated plumes make, then, mist and clusters after expansion cooling, and collide to other plumes.

In this study, an integrated ablation simulation code DECORE (Design Code for Reactor) was developed[1,2] to clarify the ability of the chamber clearance for the case of first ignition with 200 MJ power output (KOYO-fast)[3].

The formation of clusters in the ablated plume in a laser fusion reactor is evaluated numerically basing on Luk’yanchuck, Zeldovich-Raizer model[4].

Time Scale, Space Scale, and Physics

Pulse Duration of X-Ray $\rightarrow$ roughly 0.1 ns
Pulse Duration of a Particles and Ion Debris $\rightarrow$ sub $\mu$s
Length of a Plume $\rightarrow$ roughly 1 cm
  from 0 to 2 $\mu$s  ACONPL (Ablation with Condensation of a Plume)

The time that a plume reaches to the center of the chamber $\rightarrow$ sub ms
Length of a Plume $\rightarrow$ 3 m
  from 2 $\mu$s to sub ms
  CONPLH (CONdensation of a Plume with Hydrodynamics)

After Collision between Plumes (sub ms ) to 250 ms
  COLPLU (COLlisions between PLUmes)
  Radiation transport is important because plumes are heated
  by PdV Work after collision.

I calculate the time from 0 to 4.922 ms, time 0 stands heating laser is irradiated.
DECORE (Design Code for Reactor)

Atomic Process Code

- Ionization Degree, Population, Energy Level
  - Stopping Power Code
  - EOS Code
  - Emissivity and Opacity Code

- Stopping Power
- Ionization Degree
  - Pressure, Specific Heat
- Emissivity and Opacity

ACONPL (Ablation and CONdensation of a PLume)
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Phase Transition from plasma to gas to liquid (Condensation, Clusterization)

Hydrodynamics of gas (plasma)
Radiation transport of self X-ray

Interaction between X-ray, α particles, Ion debris
From burning plasmas and liquid metal, gas, and plasmas.

Phase Transitions from liquid to gas (plasma)

Read data of Ionization degree, Specific heat, Pressure, Stopping power, Emissivity and Opacity from table.
Condensation of a Plume
(Phase Transition from Gas to Liquid)

- Mass Density Dependence of Vaporization Temperature

\[ T_c(\rho) = q \Phi(\rho) \frac{1}{\Phi(\rho)^3} \exp \left[ -\frac{1}{\Phi(\rho)} \right] = B \rho \left( \frac{q^2}{T_s T_i} \right)^{3/2} \]

\( q \) : Latent Heat of Vaporization (Kelvin)

- Introduction of Effects on Condensation of a plume by Improved Luk’yanchuk Model

Condensation Rate \((y=0, \text{Gas}; y=1, \text{Liquid Droplet})\)

\[ y(x, t) = \nu(x, t) \cdot g(x, t) \]

Rate of Nucleation

\[ \frac{dX(x, t)}{dT(x, t)} = \frac{\nu \otimes T_{mc}}{\chi^2} \left( \frac{1}{\Xi_0} \right) \left( \frac{1}{\Xi} \right) N(x, t) \]

Cluster Growth

\[ \frac{d\mu(x, t)}{dt} = \frac{\nu \otimes q}{\chi^2} \left( \frac{1}{\Xi_0} \right) \left( \frac{1}{\Xi} \right) \left( \frac{1}{\Xi} \right) \]

Temperature of Clusters

\[ \frac{dT(x, t)}{dt} = \frac{\nu \otimes (T(x, t) - T(x, t))}{\chi^2} \left( \frac{1}{\Xi_0} \right) \left( \frac{1}{\Xi} \right) \left( \frac{1}{\Xi} \right) \]

Super Cooling Parameter

\[ \theta(x, t) = \frac{T_i(x, t) - T(x, t)}{T_i(x, t)} \]

Reference

B. S. Luk’yanchuk, S. I. Anisimov et. al., SPIE 3618 (1999) 434-452.
Treatment of **Phase Transition** from Liquid to Gas in ACONPL

○ Equation of Motion of Ablation Surface

\[
\frac{\partial}{\partial t} x_v(t) = \sqrt{k_B T_v / m_i} \cdot \exp\left( -\frac{m_i L_v}{k_B T_v} \right) \frac{\kappa_l}{\rho_l} \frac{\partial T(x,t)}{\partial x} \bigg|_{x=x_v} = L_v \frac{\partial}{\partial t} x_v(t)
\]

\[T_v = T_l(x_v(t))\quad T_v : \text{Temperature of Ablation Surface}\]

\[L_v : \text{Latent Heat of Vaporization}\]

○ Equation of Energy in Liquid

\[
\frac{\partial U_l(x,t)}{\partial t} = \nabla \cdot \left( \kappa \nabla T(x,t) \right) + Q_p(x,t) + Q_x(x,t) + Q_{\text{rad}}(x,t) \quad x_v < x < x_{\text{max}}
\]

\[U_l(x,t) = \rho_l \left\{ \int_{x_0}^{T(t)} C_l(x,T(x,t)) \, dT + \Delta_l(x,t) \right\} \quad Q_p : \text{Heat quantity due to charged particles}\]

\[U_l^{\text{crit}} = \rho_l \left\{ \int_{T_{\text{vap}}}^{T_v} C_l(x,T) \, dT + L_v \right\} \quad Q_x : \text{Heat quantity due to absorption of X-ray}\]

\[T_{\text{vap}} : \text{Vaporization Temperature}\]

If \( U_l > U_l^{\text{crit}} \), Peeling will occur.
1 Fluid and 2 Temperature Model

\[
\frac{d\rho(x,t)}{dt} = -\rho(x,t)\nabla \cdot \mathbf{v}(x,t) \quad \rho(x,t)\frac{d\mathbf{v}(x,t)}{dt} = -\nabla \left[ P_e(x,t) + P_l(x,t) + P_{nv}(x,t) \right]
\]

\[
\exists (xt) \frac{dTx(x,t)}{dt} \quad 2I \times 22(I \times x) \quad \psi(\ ) \quad ( \ ) \quad ( \ ) \quad ( \ ) \quad ( \ )
\]

\[
+ \exists (xt) P_{xt} (xt)
\]

\[
\exists (xt) \frac{dTx(x,t)}{dt} = 2I \times +2( \ ) \quad \psi(\ ) \quad ( \ ) \quad ( \ )
\]

\[
2 + \exists (2I \times xt)\psi(cT(x,t)) \quad ( \ ) \quad \psi(\ ) \quad ( \ ) \quad ( \ ) \quad \frac{dxy^2}{dt}
\]

\[P_{nv} : \text{Numerical Viscosity}\]

4-th term of right hand side is temperature increment due to phase transition from gas to liquid (clusterization).
Irradiated Intensity of $\alpha$ particles and Ion Debris on the Wall

Time evolution of Ablation Depth
Number Densities of Particles, Clusters in a Plume
Diameters and Condensation Rates of Clusters

![Graphs showing number densities, diameters, and condensation rates over time.](image-url)
Number Densities and Velocities of Particles, Diameters and Number Densities of Clusters, When a plume reaches to the center of the chamber.
Initial Profiles on the Calculation between Plumes

Schematic Diagram on Phenomena in KOYO-fast Chamber.

Calculation Geometry

Time(0) = 0.21687 ms

Number Density of Particle (cm$^3$)

Velocity (km/s)

Density
Results on Collisions between Plumes (10 µs)

PdV work and Radiation Cooling
Results on Collisions between Plumes (0.11 ms)

Shock waves propagate to first wall of chamber.
Results on Collisions between Plumes (1.11 ms)
Results on Collisions between Plumes (4.6406 ms)

Deposition of cluster to liquid wall will be occurred.
Results on Collisions between Plumes (4.9220 ms)
Time development of Remaining Particle Mass Density

\[ \rho_i = 11.342 \, \text{g/cm}^3 \]

- \( 3 \times 10^{16} \, \text{cm}^{-3} \)
- \( 3000 \, \text{erg/cm}^3 \)
- \( 2.25 \, \text{Torr} \)