Simulation Study on Evacuation and Effects of Metal Vapor in Laser Fusion Liquid Wall Chamber

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Abstract. Simulation studies on evacuation process in liquid wall chamber have been carried out. The evacuation speed in liquid wall concepts is a critical issue for pulse repetition rate. Then we have analyzed the evacuation process in high vacuum region using DSMC code, which solve the Boltzmann equation. The simulation results of the DSMC code show that the effect of viscosity can't be neglected in the region where the gas pressure goes down to 10^{-3} ~ 10^{-4} Torr, near the saturated vapor pressure. When the surface temperature of liquid wall is adequately cooled, the evacuation speed from 10^{-2} to 10^{-4} Torr is rather fast because of the gas flow to the wall. A preliminary estimation on the influence of chamber gas to the performance of a fuel pellet and trajectory of pellet injection is carried out to identify the required level of residual gas pressure.

1. Introduction

Design studies and economic analysis of laser fusion power plants show that it is necessary to achieve pulse repetition rate of more than 3~10Hz for economically attractive power plants [1]. This pulse repetition rate is limited by the time of restoring chamber environment, as the residual gas at the time of the next pellet injection may disturb the trajectory of the injected pellet and the laser beam propagation. Then the pulse repetition rate of the liquid wall chamber concept is limited by evacuation speed of metal vapor that is ablated from liquid metal wall with the x-rays and the plasma produced by fusion burning.

The requirements for the vapor pressure not to disturb pellet injection and laser irradiation are considered to be less than 10^{-2}~10^{-3} Torr [2], [3]. The analysis of gas dynamics how the ablated liquid metal behaves and interacts with the first wall has been carried out, but the analysis in rather high vacuum region, less than 10^{-2}~10^{-3} Torr, has not been performed yet.

The regime between continuum and rarefied flow is divided by Knudsen number (ratio of the mean free path to the characteristic dimension L). When the local Knudsen number is larger than 0.01, the flow should be treated as rarefied one and be solved by Boltzmann equation. The KOYO reaction chamber [3] has cylindrical geometry with 4 m radius and 16 m height. In that chamber design, the maximum temperature of coolant materials is 550 C that the cavity pressure can decrease to the $1\text{x}10^{-4}$ Torr in the case of using lead for cooling materials. The mean free path of this condition is 0.45 m. Taking the chamber radius for characteristic dimension, the Kn number is 0.12. This is the limit of using continuum model. Therefore the gas dynamics in the cavity at $1\text{x}10^{-2}$ ~ $1\text{x}10^{-4}$ Torr have to be solved Navier Stokes equation or Boltzmann equation.

Then we study the evacuation process in the above vacuum region using the DSMC (direct simulation of Monte Calro) method, which solve the Boltzmann equation. The DSMC method is a well-established technique for modeling rarefied flows. To evaluate the results of DSMC code, we also simulate it using the TSUNAMI code, which considers the flow as continuum and solves the Euler equation [4] [5].

2. Simulation Methods

2.1 DSMC Methods

The DSMC method, which solves the Boltzmann equation with decoupling the molecular motion from collisions, has the following advantage.

-DSMC method is applicable in both the free molecular and continuum flow regimes.

-The boundary conditions are easy to set and applicable.

The collision process is calculated by the null-collision method. The flow regime is cylindrical assuming the symmetry to axis as reaction chamber KOYO, and adopt the Riechelmann-Nanbu method [6].

2.2 Boundary Conditions and Initial Conditions

The molecular interaction between liquid metal film and gas molecule is studied to obtain condensation ratio. The condensation ratio is the probability whether an incident particle is trapped in the liquid film or not. This depends on the absorption surface condition and temperature. It is difficult to estimate the condensation ratio experimentally, so that the analysis using MD (molecular dynamics) simulation has been performed. Tsuruta [7] reveals the condensation ratio has a strong dependence on the velocity vertical to the interface, and applies the results of MD simulation to the boundary conditions of DSMC method, where the condensation ratio α_c is given as a function of vertical velocities ;

$$\alpha_c = \alpha\left\{1 - \beta \exp\left(-\frac{mV_z^2}{2k_B T_c}\right)\right\}$$

Here, m is molecular mass, V_Z is the molecule velocity ingredient to interface, k_B is Boltzmann constant, and T_c is interface temperature. The α and β are parameter derived from the MD simulation. In the KOYO design study, the maximum temperature of cooling materials is considered about 550°C. If the time scale of cooling liquid surface is short, the temperature of liquid surface would decrease to near the cooling material temperature by the time when the cavity pressure goes down to the $1\text{x}10^{-2}$Torr, but the time scale of heat conduction is not so short. Then we consider the following three cases on the liquid surface temperature.

Case1: The temperature of liquid surface is same as coolant temperature 550 °C

Case2: Cooling only by thermal conduction (2mm thick liquid film cooled by coolant)

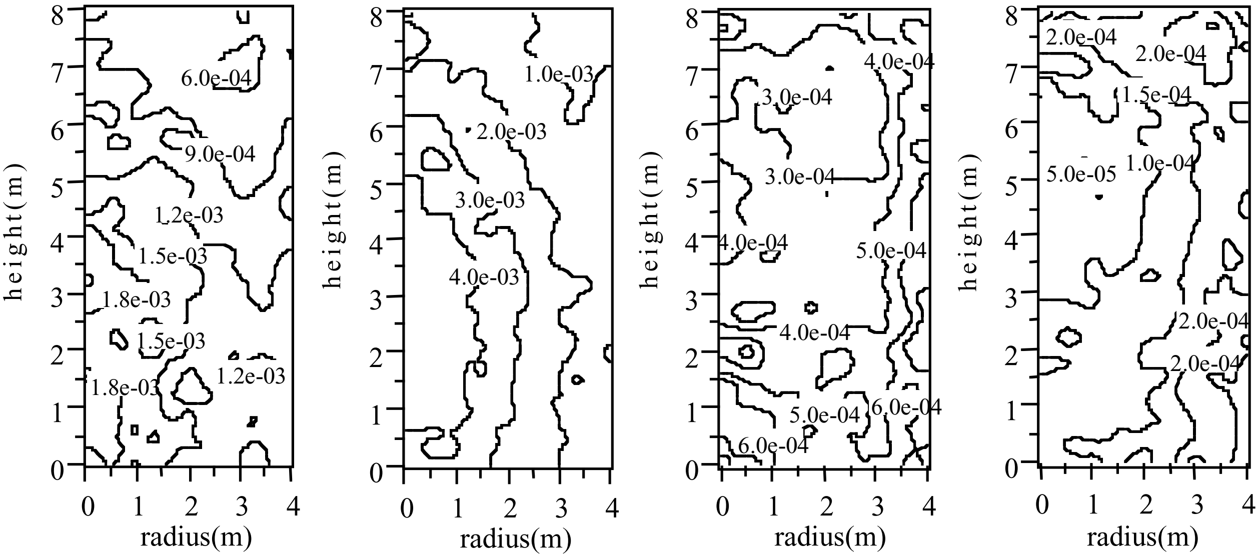
Case3: The surface temperature of side walls are same as case2, while those of the upper and bottom walls are cooled to coolant temperature 550 °C.

In order to study the evacuation process in the vacuum region, less than 10^{-2}~10^{-3} Torr, we discussed the gas dynamics after gas pressure goes down less than 10^{-2} Torr. To simplify and clarify the problem, we assume the initial condition that the gas in the chamber is uniform and static. The velocity of molecules is derived from Maxwellian at the temperature 1000°K, which gas temperature is roughly estimated by KOYO design study.

3. Results

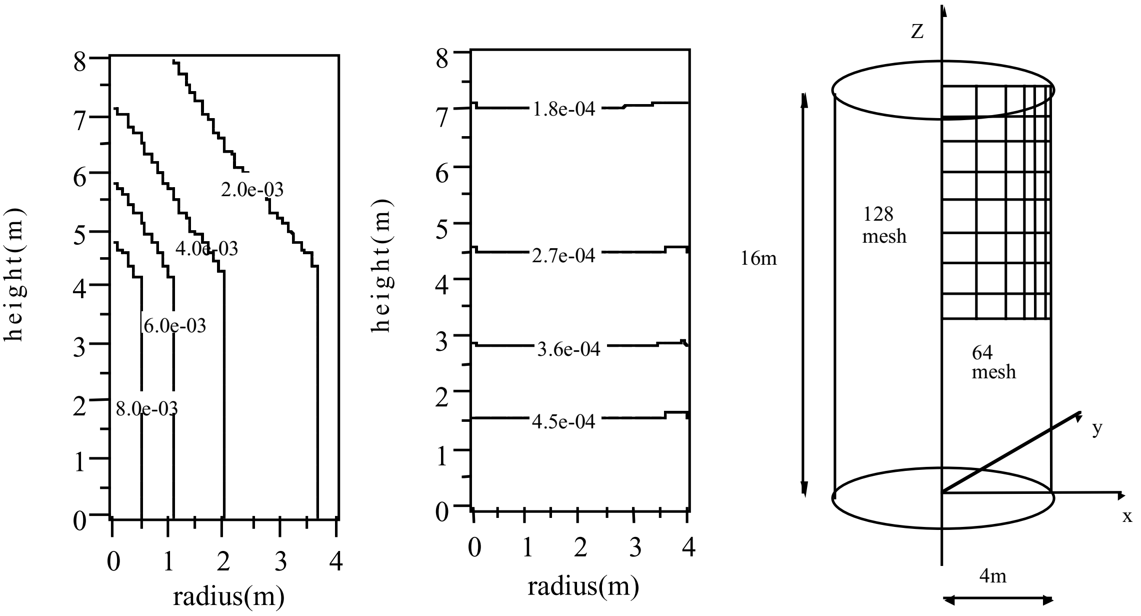
Fig.1 and Fig.2 show the chamber gas pressure distributions simulated by DSMC code and TSUNAMI code (case1). The rarefaction waves arrive the center after 20 milliseconds with the sound speed (Fig.1(a)). In the cylindrical geometry, the pressure gradient along the axial direction remains longer. Along this gradient the gas flows until it gets equivalent to the saturated vapor pressure. Fig.3 shows the average gas pressure by DSMC code and TSUNAMI code.

Compared Fig.1(c) to Fig.2(b), the effect of viscosity is prominent. The effect of the viscosity prevents the flow in the axial direction in DSMC code. In TSUNAMI code, which doesn't include viscosity, the flow in the axial direction is not disturbed and has much higher velocity to the wall than that in DSMC code, so it takes more time to come to a stop.



(a) after 20 msec (b) after 25.8 msec (c) after 30msec (d) after 51msec

Fig.1 The chamber gas pressure distributions simulated by DSMC code.



(a) after 20 msec (b) after 40 msec (c) KOYO chamber geometry

Fig.2 The chamber gas pressure distributions simulated by TSUNAMI code,
(a) after 20 msec, (b) after 40 msec, and (c) KOYO reaction chamber geometry.

The above results indicate the gas flow around the pressure 10^{-3}~10^{-4} Torr is sensitive to the boundary condition. Therefore proper boundary condition is required for exact study. To discuss the effect of the wall surface temperature we examined the above 3 cases. Fig.4 shows the average chamber pressures in case1, 2, and 3. The pressure in case 2 goes down very slowly, as the surface temperature of liquid film is not quickly goes down (620°C at after 0.1sec).

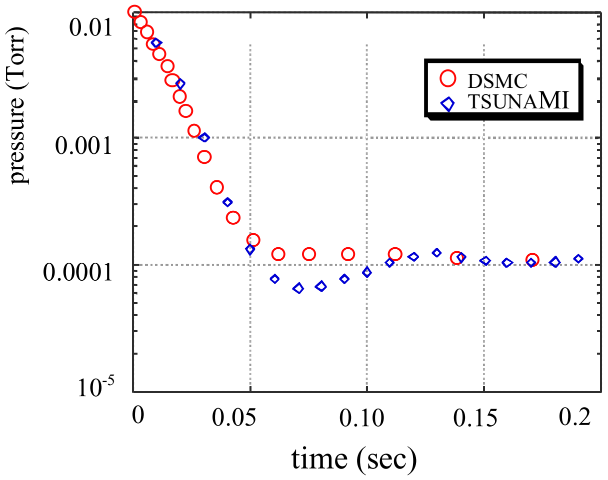


Fig.3 The average gas pressure by DSMC code and TSUNAMI (case1: surface temperature550 ℃)

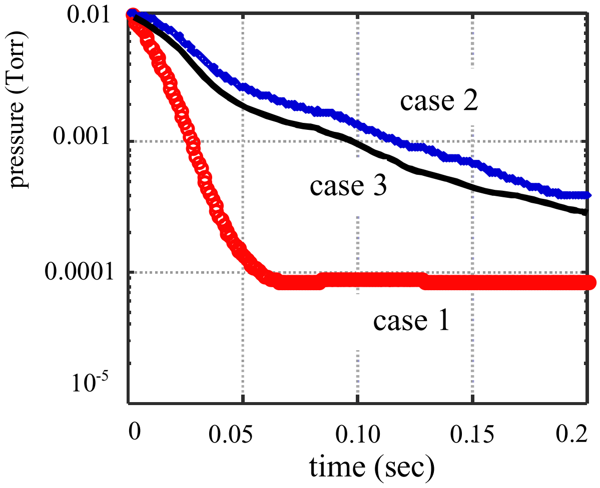
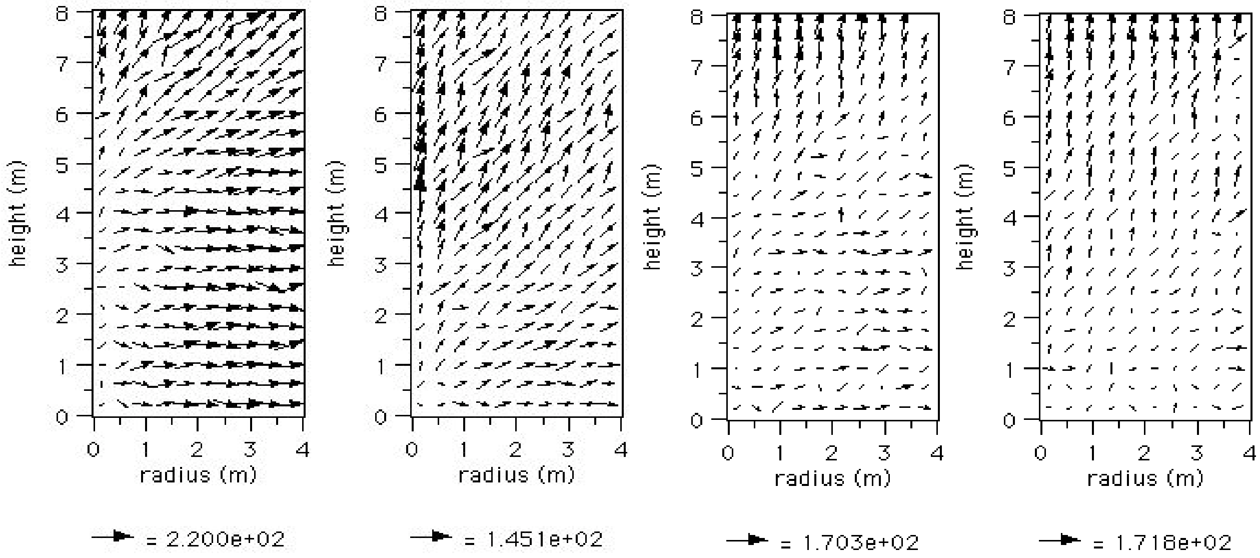


Fig.4 The average gas pressure by DSMC code (case1 and case2)

Fig.5 shows the velocity of the gas flow in the case1 and case3. The axis direction flow is weakened by radial flow in case3, compared to case1.



case1 (20msec) case1 (50msec) case3 (20msec) case3 (60msec)

Fig.5 The velocity of gas flow in chamber (case1 and case3, velocity m/sec)

The evacuation speed in case3 is not so fast, even if the upper and bottom wall surface are cooled enough, because the axial flow slows down with the viscosity near the side wall. Furthermore, the flow from side wall to center generated by radial pressure gradient, disturb axis direction flow and prevent the expansion axial flow.

4. Effects of Chamber Gas for Pellet Injection

We estimated the influence of residual gas in the laser fusion chamber on the performance of a fuel pellet [2]. One dimensional simulation for the thermonuclear gain showed that the thickness of the deposited lead should be less than 0.16 μm because of the gain reduction due to the preheat of the fuel by X-rays. To meet this requirement, the vapor pressure in the reactor should be, at least, less than 0.1 Torr. When we consider the uniformity of deposition, this requirement should be more severe and a spin of the target around the axis perpendicular to the injection axis is necessary.

After the injection at 150 m/s into the gas flow of 0.1 Torr and 30m/sec velocity, the pellet is decelerated by the drag force of the vapor. The spatial delay of the dragged pellet at the firing position is 37 mm. Since the repeatability of the vapor pressure seems poor, the firing timing of the laser should be detected near the chamber center. The influence of the crosswind on the pellet trajectory seems to be the most critical issues. Even if the vapor pressure is less than 0.1 Torr, the shot-to-shot variation of the crosswind velocity must be less than 0.8 m/s to satisfy the deviation of the pellet at the center < 100 μm.

5. Conclusions

We estimate the evacuation speed in the KOYO reaction chamber for achieving less than 10^{-2} Torr by using DSMC code, which solves the Boltzmann equation in probabilistic way. Comparing the results of TSUNAMI code solving Euler equation, We found that the effect of viscosity can't be neglected. Namely, the gas dynamics in the region where the gas pressure goes down to $10^{-3} \sim 10^{-4}$ Torr, near the saturated vapor pressure, has to be treated as rarefied flow. For the different surface cooling conditions, simulation results show the following. When the liquid surface temperature is adequately cooled, the evacuation speed is sufficiently fast. But when the side wall surface temperature doesn't go down quickly, the flow to cooled wall is disturbed with the viscosity near the hot wall. The residual gas flow may disturb the trajectory of the pellet injection severely. Then the design study and simulation study for adequate control of liquid free surface, in regard to temperature and formation geometry, is very important.

References

[1] Y.Kozaki, et al., 17th IAEA FEC, IAEA-CN-69/FTP/18, Yokohama, Japan, 1998.
[2] T.Norimatsu, to be published.
[3] Y.Kozaki, et al., Proc. 7th Int. Conf. on Emerging Nuclear Energy Systems, pp.76, 1994.
[4] R.W. Moir, Fusion Technology 19, pp.617-623, 1991.
[5] M.Kabetani, et al. Proc. AHPLA 99, November1999.
[6] D. Riechelmann and K. Nanbu, Monte Calro Direct Simulation of the Taylor Instability in Rarefied Gas, Phys. Fluids.
[7] T. Tsuruta, H. Tanaka, and T. Masuoka, J. Mech. Soc., pp. 456-462, 1998