Analysis of a core plasma dynamics and dry wall chamber for fast-ignition IFE power plant

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Abstract. Fast ignition scheme in laser fusion enables the sufficient pellet gain for a commercial operation (G~100) with small input energy. To make full use of this property, a new design concept, Fast ignition Advanced Laser reactor CONcept with a Dry wall chamber (FALCON-D), was proposed. In this paper, the analysis result of the core plasma dynamics and the thermomechanical response of the dry wall are discussed. For the former analysis, we performed numerical simulations by a 1-D hydrodynamic code and demonstrated the pellet gain G=100 with the input laser energy of 400kJ. For the latter, thermomechanical analysis by a FEM code was carried out. It indicates that the temperature increase is not a concern but fatigue failure may be a problem. Other threatening effects (e.g., blistering, carbon irradiation) are also concern. Highly-engineered materials (e.g., UFG-W) can solve these problems. It is difficult to estimate accurate lifetime of the first wall due to many uncertainties in the material properties. Further quantitative analysis based on the reliable experimental data is required.

1. Introduction

One of the critical issues in laser fusion reactor design is the high heat and particle load on the chamber first wall. Most of conceptual designs of a commercial laser fusion reactor adopt a liquid metal wall because its high heat capacity can reduce chamber size. A liquid wall, however, inevitably restricts the laser repetition rate due to the metal vapor generation. In addition, there are still several engineering issues to be solved to realize such liquid wall concepts and some advanced material (e.g., SiCf/SiC) must be used for the structural material to maintain the compatibility.

The fast ignition method, however, can achieve sufficient pellet gain with small input energy. To make full use of this property, a new design concept, FALCON-D (Fast ignition Advanced Laser fusion reactor CONcept with a Dry wall chamber), was proposed [1]. FALCON-D targets a compact (R~5.6m) dry wall chamber design and a moderate electric output (~400MWe) achievement with laser repetition rate of 30Hz. In this paper, the detailed analysis of a core (i.e., the central cavity of the fusion chamber) plasma dynamics and the response of the first wall to the pulse load are discussed.

2. 1-D hydrodynamic simulation for core plasma design

To reduce chamber size, target yield needs to be minimized with keeping sufficient gain. Then we introduced the 1-D hydrocode ILESTA-1D [2], developed in Osaka University, and performed
hydrodynamic simulations to clarify the design window. Prior to the detailed calculation, we carried out a rough estimation by using a simple analytical model based on the manner described in reference [3]. Then achievable minimum target yield with keeping sufficient gain was expected to be 40MJ. Since the code is one-dimensional, the detailed physics process of fast heating cannot be reproduced. Thus the fast heating is reflected in the code as an artificial heating source in the electron energy equation. It is modelled as a homogeneous heating of electrons in core region (assuming spherical region with optical depth $\rho R=0.4\,\text{g/cm}^2$).

As shown in figure 1, it was successfully demonstrated the achievement of the pellet gain $G=100$ with the input laser energy of 400kJ (350kJ for implosion, 50kJ for heating and assuming 20% coupling of heating laser), that is in good agreement with the above estimation.

3. Thermomechanical analysis of the first wall

3.1. Temporal temperature evolution

The dry wall undergoes several threatening effects due to high heat and particle load. First we estimated temporal temperature increase by solving the 1-D heat conduction equation with temperature-dependent thermal properties. Here we adopted 1mm-thick tungsten-armed low activated ferritic steel (F82H) for the first wall because of its high engineering reliability based on many experimental data. The spectra of X-ray and charged particles were obtained from the above hydrodynamic simulation and heat generation due to them was calculated from stopping power and photoabsorption coefficient of the first wall material. Figure 2 shows the temporal temperature evolution of various depths during the first shot. It can be seen that the maximum surface temperature is around 1400K. Only very thin region (~50µm) undergoes the large temperature elevation. Figure 3 shows the temperature evolution after multiple shots. The maximum surface temperature increases with time and saturates around 1600K after 10sec (300 shots). Since this temperature is much less than tungsten melting point (3680K) and the temperature that gives an indication of roughening (2400K), temperature increase is not a concern in our design.

![Figure 1](image1.png)

**Figure 1.** Relation between the pellet gain and total injected laser energy obtained by simple analytic formulae (4 curves) with two cases for isentrope $\alpha$ and coupling efficiency of laser energy to the fuel $\eta_c$ and by the simulation result of 1-D hydrodynamic code (black circles). Design point of FALCON-D is also plotted.

![Figure 2](image2.png)

**Figure 2.** Temporal temperature evolution during the first shot at various depths.

![Figure 3](image3.png)

**Figure 3.** Temporal temperature evolution after multiple shots.
3.2. Thermal stress
We also carried out a thermomechanical analysis by using a commercial FEM code ANSYS. Figure 4 describes the model used in the calculation. Here we used a simple bilinear approximation to describe stress-strain relation in the plastic region (tangent coefficient is 667MPa) and did not consider any dynamical effect. Figure 5 shows the stress-strain behaviour of the tungsten surface during the first 5 shots. It reveals that the surface region undergoes large plastic deformation not only in heating phase but also in cooling phase. The maximum strain and the residual stress are about 0.01 and 1GPa, respectively. Though the maximum strain increased with the temperature, it is expected to saturate as the temperature saturation. These strain and stress do not lead to immediate failure, but the fatigue failure is strongly concerned due to the large plastic strain amplitude and very large number of repetition (reaches ~10^9 times in a year). Then it may be the most critical factor that determines the lifetime of the first wall. However, in this case the strain rate is quite large (ε ~10^3) and yield stress can be higher than the static loading case [4]. This effect may give a great change in the above result.

While thermal stress at the interface of tungsten and F82H is estimated to be kept below 100MPa. According to the experiment in HAPL project, the fracture stress of HIP bonded tungsten-F82H interface is 450MPa [5]. Then degradation of bonding is not a concern in this case.

3.3. Other concerns

3.3.1. Chemical and physical sputtering. In our design case, chemical sputtering is not a concern because tungsten is used. Physical sputtering is also not so concern because of the low sputtering yield of tungsten. The loss of surface tungsten is estimated to be 0.08mm/year at maximum even if we assume the conceivable maximum sputtering yield of 0.006 due to deuterons at the energy of 10keV.

3.3.2. Blistering and exfoliation. Blistering and exfoliation due to helium accumulation may cause a big problem. According to the experiment in HAPL project [6], exfoliation occurs at the helium fluence of 10^{22}/m^2 (coincides to 40at% accumulation) and surface layer with the thickness coincides to alpha particle range was lost. Since in this case helium fluence is ~10^{16}/m^2/shot and 3.5MeV alpha particle range is 5µm, it may cause 16mm/year loss, which is totally unacceptable (calculation from the threshold accumulation gives 2.1mm/year loss, which is also unacceptable). The same experiment also indicates helium desorption through enhanced diffusion by temperature increase. Diffusion of helium in the metal lattice is described by a diffusion equation with the diffusion coefficient given as

$$D = D_0 \exp \left( \frac{-Q}{kT} \right)$$

where $D_0$ is a constant depends on the material (4.7 × 10^{-7} m^2/s for tungsten) and $Q$ is the effective diffusion activation energy. The maximum diffusion coefficient is only 3.3 × 10^{-16} m^2/s in this case if we use $Q$=3.52eV obtained from the HAPL experiment [7]. Then helium is almost immobile and
desorption is hardly expected. But the use of some highly-engineered materials (e.g., ultra fine grained tungsten [8]) can enhances the helium diffusion and suppress the blistering formation.

3.3.3. Carbon irradiation Since the pellet has plastic ablator, many carbon ions also irradiate the first wall. Diffusion of the carbon ions can be also described as the form of equation 3 and D, and Q are the order of 10^-6 and ~2eV, respectively [9]. Thus carbon is also immobile and formation of tungsten carbide (WC) is inevitable. Then the change in thermomechanical properties (melting point, thermal conductivity, yielding stress, etc.) can cause the further reduction of the armor lifetime. Carbon also generates large defects in the tungsten and it can affect the helium diffusion.

3.4. Possibility of the use of alternative materials Since the maximum surface temperature is relatively low, alternative materials can be used for the first wall. We considered chromium as a candidate. It has relatively high abundance ratio and very low activation. It is favourable for the armor because it has close thermomechanical properties to F82H. It is reported to have lower diffusion activation energy of impurities than tungsten [10]. Although it has high sputtering yield and low yield strength, it can give a great impact on the first wall design.

4. Conclusion
The design possibility of a fast ignition laser fusion reactor with a dry wall chamber has been examined. 1-D hydrodynamic simulation indicated the achievement of sufficient pellet gain (G~100) with input laser energy of 400kJ (350kJ for implosion, 50kJ for heating). Thermomechanical analysis revealed the temperature increase is not a concern but the first wall surface undergoes cyclic plastic deformation and fatigue failure is a concern even in this low heat load condition. The mass loss of the armor material by other effects (e.g., exfoliation, carbide formation) is also quite severe. But high strain rate and the state of material (crack density, grain size etc.) can greatly change the results. We need to build reliable database and perform analysis in further quantitative way.

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