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New critical assessments of chamber and wall response to target implosion in inertial fusion reactors☆

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Abstract

The chamber walls in inertial fusion energy (IFE) reactors are exposed to harsh conditions following each target implosion. Key issues of the cyclic IFE operation include intense photon and ion deposition, wall thermal and hydrodynamic evolution, wall erosion and fatigue lifetime, and chamber clearing and evacuation to ensure desirable conditions prior to next target implosion. Several methods for wall protection have been proposed in the past, each having its own advantages and disadvantages. These methods include use of solid bare walls, gas-filled cavities, and liquid walls/jets. Detailed models have been developed for reflected laser light, emitted photons, neutrons, and target debris deposition and interaction with chamber components and have been implemented in the comprehensive HEIGHTS software package. The hydrodynamic response of gas-filled cavities and photon radiation transport of the deposited energy have been calculated by means of new and advanced numerical techniques for accurate shock treatment and propagation. Photon radiation transport models are developed for either the gas-filled cavity or in the evolving vapor cloud layer above the wall surface. The focus of this work is to examine the overall wall response and lifetime due to various erosion mechanisms.

Keywords: HEIGHTS; Inertial fusion; Shock hydrodynamics; Laser fusion; Chamber technology

1. Introduction

In inertial fusion energy (IFE) systems, the power to the first wall resulting from X-rays, neutrons, energetic particles, and photon radiation is high enough to cause damage and dynamically affect the ability to reestablish chamber conditions prior to the next target implosion. In the case of a dry-wall protection scheme, the resulting target debris will interact and affect the surface wall materials in different ways. This can result in the emission of atomic (vaporization) and macroscopic particles (i.e. liquid droplets or carbon flakes), thereby limiting the lifetime of the wall.

The overall objective of this work is to create a fully integrated model within the HEIGHTS software package [1] to study chamber dynamic behavior after target implosion. This model includes cavity gas hydrodynamics, the particle/radiation interaction, the effects of various heat

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sources (e.g. direct particle and debris deposition, gas conduction, convection, and photon radiation), chamber wall response and lifetime, and the cavity clearing. The model emphasizes the relatively long-time phenomena following the target implosion up to the chamber clearing in preparation for the next target injection. It takes into account both micro- and macroscopic particles (mechanisms of generation, dynamics, vaporization, condensation, and deposition due to various heat sources: direct laser/particle beam, debris and target conduction, convection, and radiation). These processes are detrimental and of significant importance to the success of IFE reactors [2,3].

2. Model descriptions

Following the micro-explosion in an IFE reactor, high-energy X-rays and ions are produced and directed toward the chamber wall at high but different velocities. Some of their energy is deposited in the residual or protective chamber gas, and is re-radiated to the wall over a relatively longer time.

As a result of thermonuclear burn in inertially confined fusion (ICF) reactors, the first wall is exposed to photon radiation and ion fluxes with a wide range of energies. The energy deposited can be calculated from various mathematical models for energy loss for each radiation type. Our HEIGHTS package contains extensive analysis of these processes, including energy deposition from photons, ions, and laser beams [2–5]. The thermal response of the chamber wall is determined if the time- and space-dependent energy depositions are known. Melting can occur in the case of a metallic wall during intense deposition of energy. The behavior of melt layers under various forces can lead to significant wall material loss [6].

Detail models of atomic physics and photon radiation transport are developed for either the gas-filled cavity or in the evolving vapor cloud layer above the wall surface [4]. These models include non-LTE multi-group for both continuum and line radiation. The hydrodynamic response of the gas-filled cavity and the resulting shock wave and its interaction with the wall have been calculated in detail using HEIGHTS [5].

Erosion by particle sputtering can be important depending on the impacting ion energy and chamber conditions [3]. A physical sputtering model has been developed to calculate chamber wall erosion due to various debris bombardments. Chemical sputtering due to formation of volatile hydrocarbon molecules (e.g. CH_4) and CO on the wall surface between incident particles and walls made of carbon-based materials (CBMs) can also be an important erosion mechanism. In addition, for CBMs, enhanced erosion yields, known as radiation-enhanced sublimation (RES), were observed during ion bombardment at higher wall temperatures above 1200 K. A model has been developed and implemented in HEIGHTS to calculate this effect as a function of wall temperature [3].

The actual condensation and deposition rate of eroded wall material will depend on both cavity conditions and the type of erosion products. The interaction and redeposition of macroscopic erosion products are complicated and initial models are being developed to assess the geometrical effects of the cavity chamber on overall net wall erosion and on cavity clearance before the next target injection.

The energy released to the wall during thermonuclear burn is partitioned among different species: reflected laser light, X-rays, neutrons, and plasma debris [3]. The plasma particles consists of both fast and debris ion fluxes. In the case of a laser-driven system, the reflected laser light from target surface can contribute to the total energy released to the wall. The energy released and spectra of the X-rays can vary over a wide range depending on target design and driver beam. Energy deposition from X-ray and fast ion and debris particles occurs near the wall surface whereas the energy of neutrons is deposited through relatively much larger material volumes.

A major goal of this study is to evaluate the effect of gas pressure on wall temperature rise and wall erosion. The energy deposition functions and wall temperature distribution are computed in great detail as a function of space mesh size to ensure accurate calculations. Previous calculations of wall surface temperatures by other authors are believed not to be correct due to this particular point [7,8].

3. Photon interaction

The primary interaction of photons with materials includes the photoelectric effect, coherent and incoherent scattering, and pair production. Cross sections for each of these reactions have been tabulated in various forms and are available for numerical calculation. The HEIGHTS-IFE package calculates the volumetric energy deposition for a given X-ray spectrum or monoenergetic photons [3]. The deposition of X-rays into first wall materials will strongly depend on the energy spectrum of these X-rays. Soft X-rays deposit their energy within a micrometer of the wall's surface, very rapidly heating a thin layer of the first wall to a higher temperature. Harder X-ray energy spectra penetrate relatively longer distances into the material, therefore, heating a larger mass to a lower temperature.

HEIGHTS-IFE numerical simulation results of target implosion were obtained using the NRL direct drive target spectra [9]. Two candidate wall materials, i.e. carbon-fiber-composite (CFC) and tungsten were analyzed. The CFC (low-z) allows X-rays to penetrate much deeper than in tungsten (high-z) and as a result, a lower temperature rise in CFC materials is expected. The HEIGHTS package can also study the chamber wall response of a multi-component structure [2,3].

4. Ion interaction

Ion deposition calculations are performed using several models to predict the slowing down behavior of incident ion fluxes in various candidate materials. The interaction of charged particles with materials is primarily due to two processes. The first is between the incident ion and the electrons of the wall material, which is an inelastic collision. The second interaction is collision of the ions with wall material nuclei, which is an elastic interaction. The dominant mechanism of ions slowing down in materials is dependent upon the instantaneous energy of the moving ion. Several methods are used in our HEIGHTS calculations for deposition and interaction of fast and slow debris ions in various wall materials. These methods have been compared, and the range of validity of each method is well-established [3].

By using various fluxes of fast and debris ions obtained from the NRL direct drive target spectra [9] as a result of target implosion, HEIGHTS-IFE calculates the energy loss of ions in uniform or composite chamber wall, that is needed for its detail thermal evolution [3].

5. Thermal evolution of the chamber wall

The rapid heating of first-wall components due to X-ray and ion debris deposition in ICF reactors may lead to melting and subsequently to surface evaporation. HEIGHTS-IFE solves the heat diffusion equation subject to several boundary conditions. An accurate analysis of this problem initially requires the solution of at least two moving boundary problems [3]. A moving front where vaporization occurs becomes one boundary and a second moving boundary is internal between the liquid and solid interface.

The wall time evolution starts from the arrival of the X-rays, then the reflected laser lights, then the neutrons, then the fast and slow ion debris. In the case of a gas-filled cavity, the re-radiated absorbed gas energy in the form of soft X-ray energy is important and is taken into account [4]. The radiated energy depends on the fine details of the atomic physics and radiation transport methods used. Fig. 1 shows the percentage of the radiated energy flux from a 50 mTorr Xe gas pressure as a function of time. Line radiation and line splitting is a very important factor in correctly modeling gas response to thermonuclear reaction [4].

The surface temperature is determined both from boundary conditions and kinetics of the evaporation process [3]. The surface temperature of a carbon wall material is presented in Fig. 2. This calculation is for a bare-wall concept with and without gas protection and for the lower yield

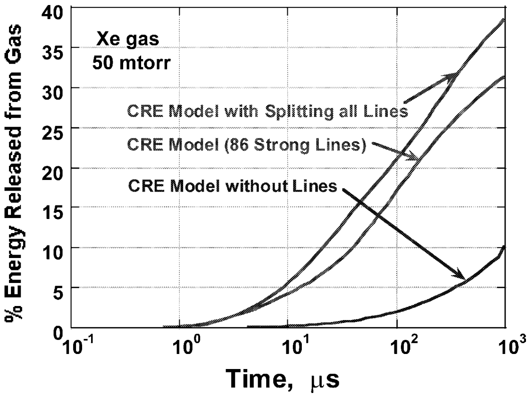

Fig. 1. Time-dependent energy released from Xe gas.

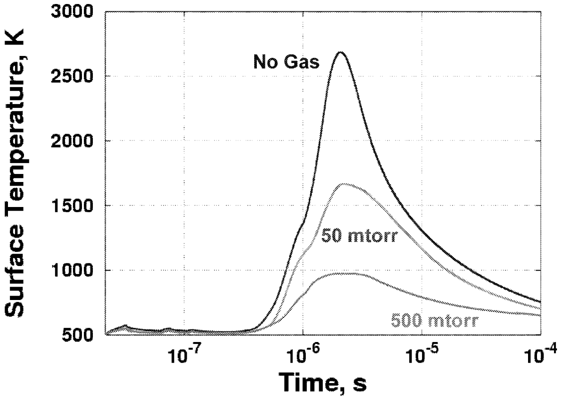

Fig. 2. Surface temperature rise in graphite at different gas pressure.

NRL direct target spectra [9]. Fig. 2 also shows the time evolution of the wall thermal response due to the sequence of different incident species. Higher gas pressures significantly reduce the wall temperature rise by absorbing part of the incident energy of X-rays and ions. However, insufficiently cooled gas due to this absorbed energy prior to next target injection, particularly near the center of the chamber, will significantly affect target integrity and ignition.

6. Erosion processes

The erosion mechanisms of debris/surface interaction include physical sputtering, chemical sputtering, and RES. Physical sputtering yields and their dependence of the incident ion energy, mass, and angle have been studied theoretically, experimentally and by computer simulation programs, such as the ITMC Monte Carlo code (part of the HEIGHTS package) [1]. High-z materials, such as tungsten, show low sputtering yield at low ion energies and, therefore, may be the preferred choice. For higher ion energies and low-z materials, such as lithium, beryllium, or CBMs, the sputtering is less critical, but chemical erosion for CBMs may become important and cause additional wall erosion.

The relatively high incident particle energies in the ICF condition will likely cause lower sputtering yields. However, if a gas is employed for cavity protection without sufficient density to stop these energetic ions, it may result in higher sputtering erosion.

In contrast to physical sputtering, chemical erosion strongly depends on the wall surface temperature. For hydrogen irradiation of carbon, the chemical sputtering significantly depends on wall temperature and the incident energy. Chemical erosion yield reaches its maximum around 800 K. At low ion energies (<100 eV), the maximum decreases and the temperature dependence becomes broader such that at room temperature the chemical sputtering yield may exceed the values of physical sputtering [10]. The exact values of chemical sputtering of hydrogen isotope ions incident at very high energies is not known due to the deep penetration of these ions into wall materials. For graphite, besides erosion by chemical sputtering, enhanced erosion yields were measured for ion bombardment at target temperatures above 1200 K [11]. This RES occurs when interstitial atoms formed by the incident particles diffuse to the surface and then sublimate.

Fig. 3 shows HEIGHTS-IFE simulation of various erosion mechanisms of graphite for the NRL direct target case [3]. Shown separately are the erosion rates caused by both fast and debris protons. It can be seen that erosion due to physical sputtering is at least two orders of magnitude lower than chemical erosion and RES. In the case of graphite wall, chemical erosion and RES remain major erosion mechanisms, more than two orders

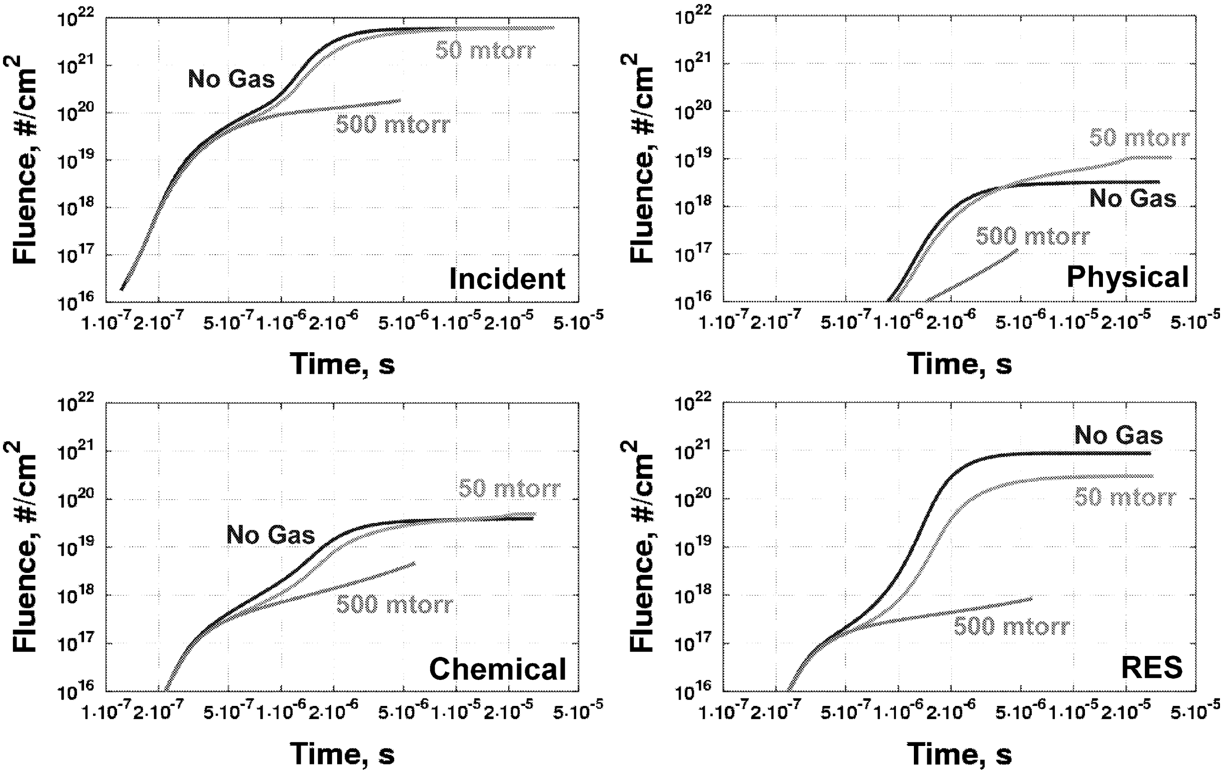

Fig. 3. Fluency of major graphite erosion mechanisms at different gas pressure.

of magnitude higher than erosion by physical sputtering. Despite that tungsten wall lacks both chemical sputtering and RES, its physical sputtering erosion still significant and can play a very important role in the total erosion yield [3].

HEIGHTS integrated results of wall thermal response and erosion are the first detail analysis of this problem and differ than other codes radiation hydrodynamic calculation [7,8] since such calculations used either simple radiation physics and/or incorrect numerical methods that can lead to large errors and wrong results.

7. Macroscopic erosion products

Modeling predictions indicate that surface vaporization losses of metallic materials can be lowered by different protection schemes. However, for liquid metal surfaces, ablation is predicted theoretically to be in the form of macroscopic metal droplets due to splashing of the molten layer [6]. Laboratory experiments to predict erosion of wall materials during a plasma disruption in magnetic fusion systems have also shown that erosion of metallic materials (such as W, Be, Al, and Cu) can be much higher than mass losses due only to surface vaporization. Such macroscopic ablation occurs as a result of splashing of the liquid layer, mainly caused by boiling and explosion of gas bubbles in the liquid, absorption of debris momentum, and hydrodynamic instabilities developed in the liquid layer [1]. Nonmetallic materials such as graphite and CBMs have also shown large erosion losses, significantly exceeding that from surface vaporization. Therefore, more relevant experimental data and additional modeling are needed for inertial fusion devices to evaluate the erosion of CBMs, which strongly depends on the type of carbon material.

The ejected macroscopic particles will form an aerosol cloud near the target surface. Therefore, accurate calculations of mass losses require a full description of the media near the wall surface, which consists of a mixture of vapor and droplets/macroscopic particles moving away from the surface. These processes are quite important in evaluating chamber cavity clearing conditions prior to next target injection.

Fragmentation models of thick liquid walls/jets proposed as an alternative to gas protection method have also been developed and implemented in HEIGHTS [12]. The strong shock waves initiated in the thick liquid wall as a result of neutron deposited energy will lead to severe destruction of the thick wall. The produced fragments with very high velocity will seriously impact the chamber clearing dynamics required prior to next target injection as well as on the wall lifetime.

8. Conclusions

Models have been developed to study the dynamic behavior of ICF cavities following target implosions. These models take into account energy deposition from the reflected laser light, emitted photons, neutrons, and target ion debris and the interaction/thermal evolution of chamber gas/wall components and are implemented in the comprehensive HEIGHTS-IFE package. The hydrodynamic response of gas-filled cavities and photon radiation transport of the deposited energy can also be accurately calculated as a result of the deposited energy.

Several erosion-causing mechanisms are modeled and evaluated for assessing chamber wall lifetime. These erosion mechanisms include vaporization, chemical and physical sputtering, RES, melt/liquid splashing, and macroscopic erosion. Depending on target yield and cavity gas pressure, most of these erosion mechanisms could be important factors in determining the best choice material and the overall lifetime of chamber walls in IFE reactors. While gas-filled cavities may mitigate the effect of direct energy deposited at the wall, higher physical and chemical erosion can result. In addition, an insufficiently cooled gas prior to next target injection can significantly affect target integrity and ignition. Violent fragmentation of thick liquid walls/jets due to neutron energy deposition may seriously impact cavity clearing dynamics prior to next target injection. No obvious cavity protection mechanism is identified. More detailed analysis is needed to determine if inertial fusion is a viable source of energy and economically feasible.

Acknowledgements

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