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Research Article

Analysis of hohlraum energetics of the SG series and the NIF experiments with energy balance model

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Abstract

The basic energy balance model is applied to analyze the hohlraum energetics data from the Shenguang (SG) series laser facilities and the National Ignition Facility (NIF) experiments published in the past few years. The analysis shows that the overall hohlraum energetics data are in agreement with the energy balance model within 20% deviation. The 20% deviation might be caused by the diversity in hohlraum parameters, such as material, laser pulse, gas filling density, etc. In addition, the NIF's ignition target designs and our ignition target designs given by simulations are also in accordance with the energy balance model. This work confirms the value of the energy balance model for ignition target design and experimental data assessment, and demonstrates that the NIF energy is enough to achieve ignition if a 1D spherical radiation drive could be created, meanwhile both the laser plasma instabilities and hydrodynamic instabilities could be suppressed.

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Keywords: Energy balance model; Hohlraum energetics; National Ignition Facility (NIF); Shenguang (SG) series

1. Introduction

Indirect drive inertial confinement fusion (ICF) uses a high-Z hohlraum (cylindrical [1,2], rugby or elliptical [3,4] or spherical [5,6] hohlraum) to convert the incident laser energy into thermal X-rays, which ablate a capsule located at the hohlraum center to achieve thermonuclear ignition. A successful indirect drive ignition requires driving the implosion capsule to high velocity (~370 km/s) while keeping the cryogenic deuterium–tritium (DT) fuel layer at low entropy [2], meanwhile the imploded core must remain nearly spherical to avoid quenching the ignition of the central hotspot via minimizing the cooling mechanisms, as well as to avoid decreasing the conversion efficiency of the implosion kinetic energy into hotspot internal energy [7]. The implosion of ignition gives stringent requirements of high velocity, low entropy and very high symmetry, which must be met by delicately adjusting the radiation environment inside the hohlraum. Therefore in ICF study, the hohlraum plays a crucial role in delivering the stringently-required radiation drive and symmetry within the limitation of the energy and power of the laser facility.

The National Ignition Facility (NIF) in the US is configured to achieve laser driven ICF via indirect drive (ID) approach [1] by using cylindrical hohlraum. Since its completion in 2009, various ignition relevant experiments using different targets and laser pulses have been carried out on the NIF. The highest neutron yield achieved so far is ~10^{16} and obvious alpha particle heating of the hotspot has been observed [8,9]. In the observation, the hotspot pressure has reached 200 Gbar compared to the ignition threshold of 350 Gbar (1 Gbar = 10^8 MPa). Nevertheless, the primary goal of achieving ignition on the NIF has not been reached yet. According to further studies on NIF experiments, many problems

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might be responsible for the failure of ignition, such as the hohlraum energetics, the low mode drive asymmetry and the hydrodynamic instability growth during the implosion, etc.

Among these possible problems, the hohlraum energetics is primary because it determines the radiation drive onto the capsule. Usually, the radiation drive incident on the capsule cannot be measured directly, thus it is often inferred from the directly observed experimental data combined with numerical modeling. Such measurements include the observation of the X-ray flux flowing out of the laser entrance holes (LEHs) at certain angles, and the measurement of the implosion trajectories of the capsule with backlit radiography. However, these measurements involve some complicated details not yet clarified [10]. For example, when measuring the X-ray flux from the LEH with the multiple-channeled X-ray diode detector (XRDs or DANTE), the interpretation of the measuring results is directly influenced by the dynamic LEH closure [11], which is hard to be precisely depicted. In addition, the radiation drive (or radiation temperature) inferred from different methods are not always in agreement with each other, and in many cases especially in the gas-filled hohlraum (GFH), the measured drive onto the capsule are well below the numerical prediction, which is called the 'energy deficit' [10,12] problem. All these complications indicate that an overall picture of the radiation drive in the NIF experiments is needed to better understand the general hohlraum energetics.

The apparent 'energy deficit' problem found using gas-filled hohlraums on the NIF raises one fundamental question: Is the energy of NIF sufficient to achieve ignition? To be more specific, if we were able to overcome the troubling laser−plasma interaction (LPI) issues encountered in the gas-filled hohlraum and thus able to provide quasi spherical X-ray drive, will the energy of the current NIF facility be sufficient for ignition? In this work, we applied the fundamental energy balance model to analyze the overall NIF data and see how much the overall NIF data would deviate from the energy balance model. Stepping forward from that, we will try to answer the fundamental question whether NIF's energy is sufficient for ignition or not.

Due to its conciseness in physical picture and easiness for utilization, the energy balance model is widely used in ignition target design and experimental data evaluation [1,13]. It builds up a physical bridge between the laser energy (or laser power) and the radiation drive inside the hohlraum. We used the energy balance model to analyze the hohlraum energetics in Shenguang (SG) series experiments as well as all kinds of ignition relevant NIF experiments.

This article is organized as below. In Section 2, we briefly introduce the energy balance model. In Section 3, we assess the experimental drive data with the energy balance model, which were observed on the SG series laser facilities adopting both cylindrical and spherical hohlraums. In Section 4, we analyze the NIF data with the energy balance model. Finally, we give a summary.

2. The energy balance model

The energy balance model depicts the energy flow inside the indirect drive hohlraum. When lasers enter the high-Z hohlraum, some fraction of the lasers is backscattered out of the hohlraum, whereas the majority of the laser energy is absorbed by the wall plasmas via collisional absorption as well as non-linear absorption schemes, and then converted into X-rays, which are either absorbed by the wall or the capsule, or escape through the LEH.

From the energy balance model [1], we have

$$\eta E_{\rm L} = E_{\rm Wall} + E_{\rm LEH} + E_{\rm cap} + E_{\rm r} = \sigma T_{\rm r}^4 \cdot [(1-\alpha_{\rm w})A_{\rm w} + A_{\rm h} + (1-\alpha_{\rm c})A_{\rm c}] \cdot \tau + E_{\rm r}. \quad (1)$$

here, we denote $E_{\rm L}$ as the incident laser energy, η the total laser to X-ray conversion efficiency including both the laser absorption efficiency and the laser to X-ray conversion efficiency, $E_{\rm Wall}, E_{\rm LEH}, E_{\rm cap}$ the X-ray energies absorbed by the wall, escaping from the LEHs, and absorbed by the capsule, respectively, $E_{\rm r}$ the radiation energy stored inside the hohlraum, $\alpha_{\rm w}$ the hohlraum wall albedo (reflectivity), $\alpha_{\rm c}$ the capsule albedo, $A_{\rm w}$, $A_{\rm h}$ and $A_{\rm c}$ the areas of the hohlraum wall, the LEHs and the capsule respectively, τ the equivalent duration of the laser pulse, $T_{\rm r}$ the radiation temperature inside the hohlraum, σ the Stefan parameter.

As we know, $E_{\rm r}$ is proportional to $T_{\rm r}^4 \cdot V_{\rm hohl}$, where $V_{\rm hohl}$ is the volume of the hohlraum. However, for the ICF hohlraum environment, even under the NIF ignition relevant radiation temperature range ~300 eV, $E_{\rm r}$ is less than a few percent of the total laser energy and can be neglected. Thus the energy balance equation becomes

$$\eta E_{\rm L} = \sigma T_{\rm r}^4 \cdot [(1-\alpha_{\rm w})A_{\rm w} + A_{\rm h} + (1-\alpha_{\rm c})A_{\rm c}] \cdot \tau. \quad (2)$$

The time derivative expression of the energy balance equation is also used in the hohlraum energetics study, which is called as the power balance equation

$$\eta P_{\rm L} = \sigma T_{\rm r}^4 \cdot [(1-\alpha_{\rm w})A_{\rm w} + A_{\rm h} + (1-\alpha_{\rm c})A_{\rm c}]. \quad (3)$$

The conversion efficiency η and wall albedo $\alpha_{\rm w}$ can be calculated self-consistently in radiation hydrodynamic simulations. In addition, $\alpha_{\rm w}$ can also be obtained analytically by assuming the Marshak wave approximation under certain incoming radiation temperature curve. As for the NIF ignition relevant targets, our calculation shows that η ~90% and $\alpha_{\rm w}$ ~90% during the main pulse with the peak $T_{\rm r}$ ~300 eV.

However, it should be noted that the energy balance model is not exactly accurate because the radiation temperature is not strictly homogenous, and also the area of the hohlraum, the LEHs together with the capsule vary during the laser drive and the X-ray ablation. Therefore, it is worth to examine the adaptability of the energy balance model with various experimental data of the hohlraum energetics.

3. Assessment of the drive data in SG series experiment with energy balance model

The energy balance model agrees well with the Nova 1-ns hohlraum experimental data [1]. Here, we applied the energy

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