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Thermal distribution and cooling performance of cryogenic target under stable and fluctuating cooling conditions

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ABSTRACT

This paper presents a numerical study on the thermal distribution and cooling performance of indirect-drive inertial confinement fusion (ICF) cryogenic target which requires a highly uniform temperature distribution around its capsule. Computational Fluid Dynamics, CFD models are developed for both stable and transient fluctuating cooling conditions. Experimental validation is undertaken and the predicted amplitudes by CFD simulation prove to be in good agreement with those measured in the experiments. The investigation results indicate that the He-H_2 gas filled in the *hohlraum* has quite an impact on the thermal environment around capsule, and improvements in the uniformity of capsule surface temperature can be made by either reduction of filling gas pressure or increase of He content in gas mixture. Fluctuation of cooling temperature deteriorates the uniformity of capsule surface temperature when compared with stable cooling conditions. However, the fluctuation amplitude can be attenuated to less than 10% in the presence of filling gas, and increasing the content of H_2 in filling gas gives rise to further attenuation.

1. Introduction

Due to the world's increasing energy consumption and the growing concerns for environment, a form of clean, sustainable and large-scale energy is urgently needed. Fusion, a high energy reaction in which two lighter atomic nuclei (most often deuterium and tritium, the identified best and most efficient fusion fuel) fuse to form a heavier nucleus [1], offers the potential for virtually unlimited, high density, safe and environmentally benign energy [2–5].

Fusion is the process that powers the sun and the stars, and the energy source of the universe [6,7]. For decades, it has been a scientific and engineering challenge to harness fusion as a source of large-scale sustainable energy. According to the Lawson criterion, successful fusion will be achieved when the following confinement conditions are fulfilled: very high temperature, sufficient plasma particle density and sufficient confinement time. Commendable efforts have been made to fusion confinement concepts over the years, and the current leading designs include magnetic confinement fusion and inertial confinement fusion (ICF). However, despite the rapid gains in controllable fusion research, the long sought-after energy breakeven point had not been achieved as of January 2017 [8]. In other words, it currently takes more energy to reach ignition than the fusion reaction produces.

In the inertial confinement fusion, the small capsule filled with deuterium-tritium fuel implodes at the rapid heating of laser beams (direct drive) or laser-produced X-rays (indirect drive), heats and compresses the fuel inside to very hot and dense conditions so that the self-sustaining fusion reaction can occur. The direct drive method, in principle, can be very efficient but is difficult to avoid asymmetric implosion. Instead of being hit by direct laser, the fuel capsule of indirect drive [9] is placed in a high Z *hohlraum* (gold or gold-lined uranium) and bathed in the smooth high-intensity X-rays given off from the surrounding laser-irradiated *hohlraum* wall. As compared to the original laser beams, the reemitted X-rays are distributed more evenly and symmetrically, and this makes it easier to obtain the uniformity required for good implosions. The indirect drive method was validated through the late 1980s by OMEGA and Nova lasers, and is used by systems including National Ignition Facility, Laser Mégajoule, Magneto-inertial fusion or Magnetized Liner Inertial Fusion.

Besides the extremely precisely and evenly distributed drive energy across the outer surface, the fuel capsule itself must be constructed with extremely high precision and sphericity to achieve ignition. Modern cryogenic target fuel capsule is a spherical ablator shell containing a deuterium-tritium (DT) ice layer and the central sphere of deuterium-tritium (DT) vapor [10–13]. And before the final shot, the capsule should be frozen from the DT ice layering temperature to the aim value. The roughness of the DT ice layer results in growth of hydrodynamic instabilities, which threatens the performance of the implosion and even disrupts the fuel compression [14,15]. Therefore the DT ice layer

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Nomenclature

A	Peak amplitude of temperature fluctuation, K
f	Frequency, hz
p	Gas pressure, MPa
T	Temperature, K
$T_{\max}$	Maximum temperature, K
T_O	Mean value of fluctuating temperature, K
$\Delta T_{\max}$	Maximum temperature difference around capsule, mK
t	Time, s
$v_{\max,\mathrm{U}}$	Maximum velocity of upper convection cell, mm/s
$v_{\max,\mathrm{L}}$	Maximum velocity of lower convection cell, mm/s
x_{He}	Mole proportion of He

Abbreviation

NIF	National Ignition Facility
LMJ	Laser Mégajoule
ICF	Inertial confinement fusion

is required to be uniform and smooth enough so as to minimize Rayleigh-Taylor instabilities. According to investigation of laser Mégajoule, the DT ice layer inside the capsule should have a uniformity more than 99% and an inner surface roughness less than 1 μm RMS. Fortunately, the DT layers will slowly conform to the local temperature of outer shell in a process termed beta-layering, i.e., temperatures differences outside the shell will produce mass displacements of DT layer [12]. If the outer shell is isotherm, the DT layer will also be in shape of uniform spherical shell, as required for ignition. In other words, given a spherical capsule shell and a uniform thermal environment, a uniform spherical ice layer could be produced by beta-layering over a period of time [16]. Analytical calculations indicate that controlling the temperature difference around the capsule within 0.1 mK will obtain the required uniform DT ice layer for ignition [17]. Besides the DT layer formation, experimental results [18] have shown that the surface roughness increases as the temperature is reduced even with a small cooling rate. Therefore, for indirect drive ICF target, the temperature distribution inside the *hohlraum* must be accurately controlled to ensure such an isotherm around the capsule [15].

The *hohlraum* is designed with an inner surface of Au for conversion of laser energy to X-rays, and filled with He gas or a gas mixture of He + H_2. The filling gas provides a thermal conduction path between the capsule and the *hohlraum* wall and acts as a tamping gas at the shot time. Its physical properties and thermodynamic state will have an influence on the X-ray drive symmetry as well as the capsule asymmetries. The reported values of filling gas properties from National Ignition Facility and Laser Mégajoule differ within a wide range. Take the filling gas pressure for example. Bernat et al. pointed out that the pressure of He gas filled in *hohlraum* would be controlled at 10–50 mTorr during layering [19]. However, in 2010, investigation by Kozioziemski et al. showed that the *hohlraum* was usually filled with 1–300 Torr of He gas to conductively cool the capsule [11]. And Moll reported that some target designs increased the pressure of filling gas to 700 mb (about 525 Torr) to reduce plasma expansion [20]. As to other physical properties, investigations of Moll, Moody, Bernat, Haan showed that the density of filling gas could differ from 0.01 $\mathrm{kg\,m^{-3}}$ to 3 $\mathrm{kg\,m^{-3}}$ [14,19,21,22]. Moreover, the filling gas near the capsule is heated via tritium beta decay, and becomes buoyant under the gravity. Convection is thus set up and perturbs the ideally isothermal environment around the capsule [13,14], which in turn results in a redistribution of the DT ice and significant distortions to ice layer uniformity [23]. In fact, hohlraum configuration and convection of filling gas are two major factors causing the isotherm distortion around the capsule. Therefore filling gas plays a key role in controlling the thermal environment and convection around the fuel capsule. The anticonvection baffles or films and asymmetric thermal shimming have been studied in an attempt to limit the effect of convection [20,21,24,25]. However, further studies are needed to get better understanding on the parametric effect of filling gas convection.

In the present study, numerical models have been developed to study the thermal and hydrodynamic characteristics of cryogenic target at different filling gas conditions. Investigations are also conducted on the effects of filling gas in preventing temperature fluctuation propagation from the cooling ring to capsule surface. The results can serve as a guideline for capsule temperature control.

2. CFD modelling

The cryogenic target configuration used in the present study is shown schematically in Fig. 1. It is a typical design for indirect drive ignition targets, consisting of a cryogenic fuel capsule, a gold *hohlraum* with two laser entrance holes (LEHs), and a thermal mechanical package (TMP) with heaters and cooling rings. The fuel capsule has an outer radius of 1.16 mm and is made up of concentric spherical shells, i.e. a 200 μmthick Ge-doped CH ablator shell encloses a 63 μm thick DT ice layer which in turn surrounds a central sphere of DT vapor in equilibrium with the DT ice. The capsule is held by Formvar tent and centered inside the gold *hohlraum* which has a cylindrical shape of 10 mm long and 5.44 mm in diameter. Small holes on the Formvar tent is used to insure the same pressure in each compartments of fragmented *hohlraum*. The Laser Entrance Holes are sealed by thin polyimide membranes, and laser beams pass through them to strike the inner wall of *hohlraum* and create a superhot plasma which radiates uniform X-rays. The X-rays rapidly heat the capsule ablator shell to implode the

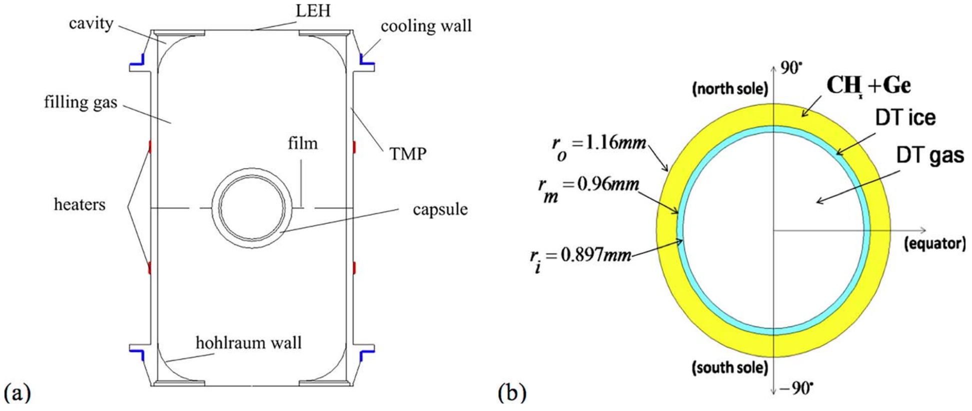

Fig. 1. Schematic diagram for (a) cryogenic target and (b) capsule.