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Numerical investigation on the temperature control of a NIF cryogenic target

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Abstract: Numerical investigation was performed on the temperature control of NIF cryogenic target in order to get a temperature uniformity of 0.1mK on the surface of the capsule. Heat transfer process was discussed to find out major factors in the temperature control, tamping gas heat transfer and free convection of the tamping gas was calculated. Spherically symmetric temperature field is required due to energy released from the tritium decay within the capsule, auxiliary heating is set on the hohlraum to compensate the higher heat loss caused by the lower tamping gas thermal resistance on the mid plane. Free convection effect of the tamping gas is reduced by separating the tamping gas with plastic films and independent temperature control of the cooling arm. This research may provide theoretical foundation and reference for temperature control on the cryogenic target.

1. Introduction

Fusion energy, as an efficient, safe, abundant clean energy, is expected to be utilized to generate electricity based on the inertial confinement fusion (ICF) nuclear power plants in the future. ICF is a method to obtain fusion energy, in which nuclear fuel can be compressed by internal implosion to reach a high temperature and density. Compared to gas capsule, the cryogenic target has a higher initial fuel density ($0.253g/cm^3$), reducing the compression energy requirements for high temperature and density with laser. So it is the preferred option in ICF. The fabrication of cryogenic capsule with high-density, uniform fuel ice thickness and smooth inner surface is the core technology to achieve fusion ignition [1]. In order to suppress the Rayleigh - Taylor instability growth and improve energy gain for ignition, the uniformity of deuterium tritium target (DT) layer thickness must be greater than 99% and the surface roughness RMS should be less than 1μm [2]. Analytical calculations indicate that thermal gradient around the capsule should not exceed 0.1mK for these requirements. Therefore, the

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temperature distribution along the cryogenic structure must be accurately controlled in order to ensure such an isotherm around the capsule [3].

In this paper, a theoretical model was established based on the indirect drive target device in the National Ignition Facility (NIF). The heat conduction model of hohlraum was established and the heat conduction and convection inside was discussed. Also, main factors of temperature control were proposed. Besides, a two-dimensional model for hohlraum was built by FLUENT and the temperature distribution of capsule surface was studied. The control method for the maximum temperature difference 0.1 mK of the capsule surface was obtained.

2. Theoretical model and heat transfer analysis

The NIF system cryogenic target is centered inside a 30μm thick gold cylindrical cavity (hohlraum), filled with an equal mixture of hydrogen and helium (H2 + He) which is used to reduce the plasma extension during laser shot and to dissipate the heat released during beta-layering [4]. The cryogenic target is made up of three layers. The outermost layer is capsule ablation layer, which is made of the Ge-doped element hydrocarbon polymer with an outer diameter of 2.32mm and a thickness of 200μm; the intermediate layer is DT fuel ice layer with a thickness of 63μm; the innermost layer is DT fuel gas [5] [6]. The cooling arm, which is connected to a refrigerator, is in contact with outer surface of the hohlraum to dissipate decaying heat.

Ignoring radiation, there are two main heat exchange ways in this model. One is the heat conduction from the capsule to the wall by hydrogen-helium mixed gas and then to the cooling arm. The other one is free convection of the H-He gas mixture under gravity. The contents below will focus on the analysis of the capsule surface temperature gradient due to the two heat transfer ways as well as the temperature control means.

3. Theoretical calculation of heating power

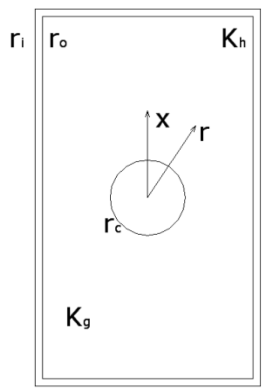

Figure 1. Theoretical model of hohlraum calculation.

In order to take the decay heat of DT gas inside the capsule out, hydrogen-helium gas mixture was filled in the hohlraum. Since the thermal resistance increases with the distance between the gas mixture and wall, the heat loss in the middle plane is larger than the two ends leading to its lower temperature. Therefore, auxiliary heating should be added on the hohlraum surface to compensate for the variation of thermal resistance.

Assuming that the capsule is in an infinite space and it's simplified as a spherical heat source in a cylindrical cavity. To fulfill the uniformity of capsule surface temperature, it is only necessary to study how to make the capsule in a uniform spherical temperature field. Figure 1 shows the simplified model of the hohlraum.

The β decay heat flux of tritium out from the capsule under steady state can be expressed as equation (1).

$$\Phi_g + \Phi_i = -k_g S dT / dr \tag{1}$$

Where S is the surface area of sphere, r is the radius of capsule, Kg is the thermal conductivity of the filled gas, Φ_g is the decay heat of the hydrogen -helium gas mixture, Φ_i is the decay heat of DT fuel ice layer.

The radial temperature distribution of the gas mixture can be expressed as equation (2).

$$T_g(r) = T(r_c) - \frac{\Phi_g + \Phi_i}{4\pi k_g}\left(\frac{1}{r_c} - \frac{1}{r}\right) \tag{2}$$

Where $T(r_c)$ is the temperature of outer surface of the ablator, r_c is the radius of the outer surface of the ablator. To get the capsule surface temperature distribution as equation (2), the temperature distribution at the junction of the hohlraum and the gas mixture should also meet this equation. Thus the interior wall surface temperature needs to be controlled to satisfy this equation.

The hohlraum is a cylinder centered with the capsule along the main axis. According to the geometric relationship shown infigure1, the center point of the capsule was chosen as the origin of coordinate x and the column coordinates of the capsule satisfy the equation $r^2=r_i^2+x^2$, where r_i is the radius of the inner wall of capsule. When it is integrated into equation (2), it can be expressed as equation (3).

$$T_h(x) = T(r_c) - \frac{\Phi_g + \Phi_i}{4\pi k_g}\left(\frac{1}{r_c} - \frac{1}{\sqrt{r_i^2 + x^2}}\right) \tag{3}$$

The heat of the capsule can only flow out from the hohlraum wall to the cooling arms at the two ends. So the radial temperature distribution is uniform and the axial temperature distribution can be derived from equation (3), shown as equation (4).

$$\Phi_h(x) = -k_h S_h dT_h / dx \tag{4}$$

Where $S_h = \pi(r_0^2 - r_i^2)$ is the cross sectional area of wall,r_0 is the outer radius of hohlraum. In order to satisfy the temperature distribution in equation (3), auxiliary heating should be added at the outer wall. The heat flux from the capsule to hohlraum wall can be expressed as equation (5).

$$q = -k_g \frac{\partial T}{\partial r} = \frac{\Phi_g + \Phi_i}{4\pi r^2} = \frac{\Phi_g + \Phi_i}{4\pi(\mathrm{x}^2 + r_i^2)} \tag{5}$$

Assuming heat flux on the hohlraum wall is q_{ext} and there is no radial temperature gradient, the hohlraum wall is a thin wall structure with large thermal conductivity.

$$-k_h S_h \frac{\partial T_h(x)}{\partial x} = \frac{\Phi_g + \Phi_i}{4\pi(x^2 + r_i^2)} 2\pi r x + \int_0^x 2\pi r_o q_{ext}(x)\,\mathrm{dx} \tag{6}$$

The equation(6) can be derived as equation(7).

$$q_{ext}(\mathrm{x}) = -\frac{\Phi_g + \Phi_i}{4\pi r_o}\left[\frac{1 - x^2(x^2 - r_i^2)^{-1}}{\sqrt{x^2 + r_i^2}}\right] - \frac{k_h S_h}{2\pi r_o}\frac{\partial^2 T(\mathrm{x})}{\partial x^2} \tag{7}$$

It can be changed as equation(8).

$$q_{ext}(\mathrm{x}) = -\frac{\Phi_g + \Phi_i}{4\pi r_o}\left[\frac{1 - x^2(x^2 - r_i^2)^{-1}}{\sqrt{x^2 + r_i^2}}\right] + \frac{(\Phi_g + \Phi_i) k_h S_h}{8\pi^2 k_g r_o}\left[\left(x^2 + r_i^2\right)^{-3/2} - \left(x^2 + r_i^2\right)^{-5/2}\right] \tag{8}$$

Heat conduction along the spherical surface is not considered in the calculation above. If the thermal conductivity of the surface material of the capsule is large, it will cause calculation error. Equation (8) shows that the amount of heating power depends on the thermal conductivity of the hohlraum material and cross-sectional area. When the thermal conductivity and cross-sectional area is increased, the power of heating required will also be increased. Therefore, to reduce the heat consumption of the cooling process, a lower thermal conductivity material and thin hohlraum wall are preferred.

Where Φ_i=4.91x10^{-2}mW/mm^3, $\Phi_{g=}$5x10^{-5}mW/mm^3, R=0.94mm, r_i=2.95mm, r_0=3mm, k_h=1080W/mK, k_g=1080W/mK, substituting the value into the equation (8), the heating power distribution along the x direction of hohlraum is shown in figure 2.

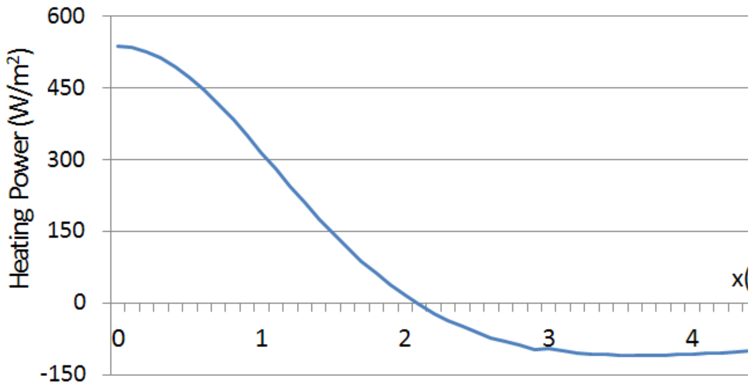

Figure 2. Heating power distribution along the x direction.

It can be seen from figure2, auxiliary heating power required in the middle plane is the largest. At the vicinity of x= 2mm, the heat flux becomes negative representing the heat needs to be removed. However, the temperature control cannot be arranged continuously along the hohlraum, so it is simplified by film heaters disposed on the hohlraum wall to provide heat in practice. The heater distribution at outer wall of the cavity will be analyzed below.

4. Numerical Simulation of temperature control

4.1 Modeling

As the hohlraum is a cylinder with axial symmetry properties, a two-dimensional model can be established and half of the structure was studied. Firstly, model mesh is generated by GAMBIT and then imported into Fluent for simulation. The total number of meshes is 90,440 among which the number of capsule meshes is 13,869. Meshes are shown in figure 3.

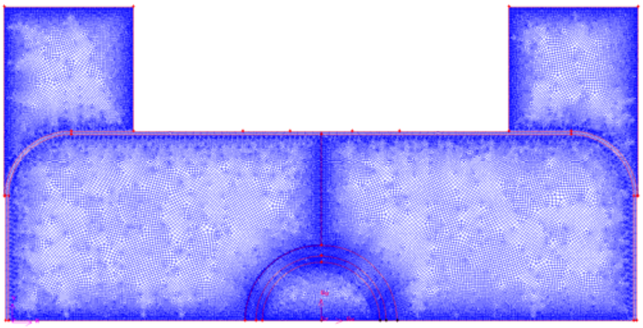

Figure 3. Mesh distribution of a two-dimensional symmetry model.

Boundary conditions set:

1) Assuming a constant temperature of cooling arm is 19.47K.
2) Reaction heat is $5x10^{-5}$ mW/mm^3 for capsule DT ice layer and $4.91x10^{-2}mW/mm^3$ for the gas.
3) Adding two film heaters in the area shown above. The cavity material is gold.
4) The cooling arm material is silicon.

4.2 Determination of auxiliary heating power

It can be concluded from the theoretical calculations in the previous section, to supplement the heat loss caused by the lower thermal resistance at the middle plane, heater should be disposed at the hohlraum surface for a uniform temperature field. And heating power needed at the middle plane is the largest. Symmetrical heating was applied in the calculation model. Two 0.75mm width film heaters were arranged at 0.5mm distance from the middle plane respectively. The optimum heating power is calculated in order to obtain the best uniformity of capsule sphere surface. At the same time, corresponding capsule surface temperature uniformity was obtained. As shown in figure 4.

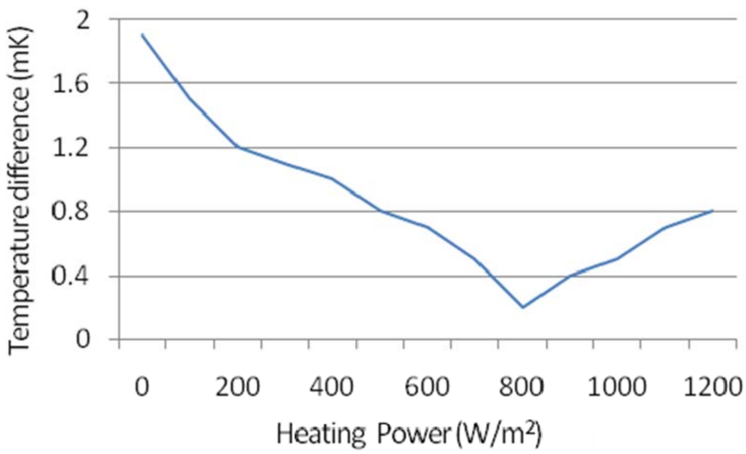

Figure 4. Temperature uniformity with different heating power.

According to the calculation results, the temperature difference at the surface of the capsule reduces by 2mK compared to the condition without auxiliary heating. When heating power is less than 830W/m^2, temperature difference at the surface of the capsule decreases with the increment of heating power. But when the heating power is greater than 830mW/m^2, the result is converse. Thus it can be concluded that there is an optimal heating power leading to the lowest temperature uniformity of 0.19mK under other constant parameters. However, 0.1mK technical standard could not be achieved by any heating power adjustment under this condition. This is due to another heat transfer factor, i.e. the free convection. The free convection will be analyzed below.

4.3 Analysis of free convection

Free convection of hydrogen-helium gas happens under gravity in the hohlraum, which has a significant impact on the capsule surface temperature distribution. In the structure discussed in this paper, the polymeric film which supports the capsule divides the gas in the cavity into two areas.

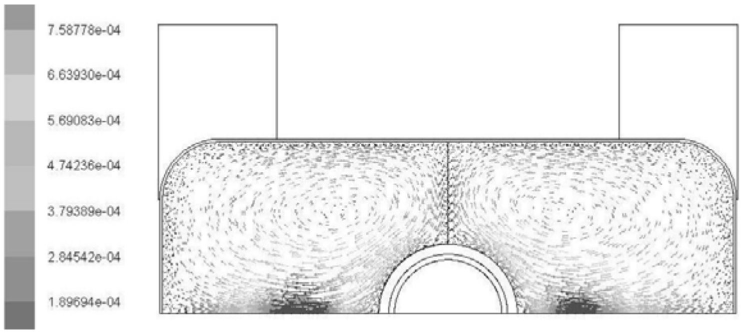

Figure 5. Velocity distribution under free convection.

Figure 5 shows distribution of the velocity vector of free convection under steady state. It can be seen from the velocity vector that heat convection is the most intensive in the upper half of the axial direction. Gas in the upper half area forms airflow near the center due to decay heating, which accelerates regional flow of the gas. On the contrary, gas in the lower half area was dispersed during ascent towards the capsule, thereby reducing its speed. Gas in the upper half area was heated during flowing down along the wall and the buoyancy increases, thus the rate of decline further reduced. When the gas flows towards the capsule, a region similar to boundary layer was formed near the capsule wall, resulting the gas temperature and thermal resistance increased. This can also be reflected by the temperature distribution at the capsule surface. At this moment, the temperature at upper capsule is higher and has a temperature difference of about 0.4mk to the lowest surface temperature.

The main characteristic number for measurement of free convection is Grashof number, which is a measurement of the ratio of buoyancy to viscous force acting on the fluid. Where g is the acceleration of gravity, l is characteristic length of the fluid region, vi s the kinematic viscosity of the fluid. We have several ways to limit free convection effect on DT ice thermal stability by reducing the g, l and v. In this paper, a heating was placed on the lower cooling ring to create a small thermal gradient on the cavity to protest gravity so as to suppress the development of free convection in the way of reducing g. By several calculations, the results show that temperature uniformity at the surface is best when the temperature difference between the upper and lower armsis1mK. The results are shown in figure6.

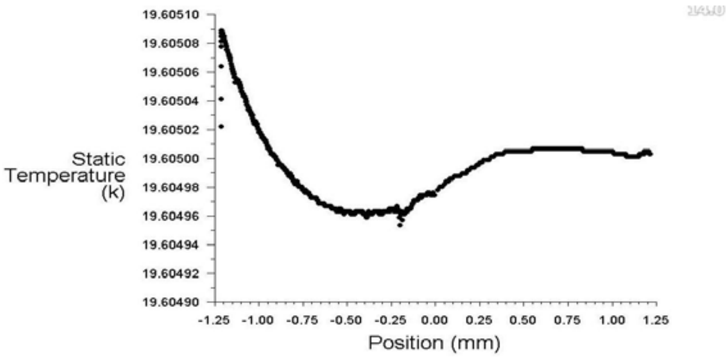

Figure 6. Temperature uniformity with different cooling arm temperature.

As can be seen from the results, the temperature at upper capsule surface is still the highest. But the temperature uniformity is improved to be 0.25mK. Obviously, the temperature uniformity can be effectively improved by increasing the lower arm temperature, though yet failing to meet the system requirements for ignition. Prior to this study, some researchers divided the fusion cavity into several sub regions, which reduces the characteristic length of the fluid and suppress the impact of heat convection effectively. However, this method is more complex. In our study below, the heating power of auxiliary heating device was set separately.

4.4 Asymmetric heating controls

Separate control of auxiliary heating power was analyzed in this section. By repeated simulations, it's found that an auxiliary heating power of 950W/m^2 for the upper half with the arm temperature of 19.4680K and 700W/ m^2 for the lower with the arm temperature of 19.4707K are proper. This is because the temperature difference between upper hohlraum wall and the capsule surface was weakened by the increment of the upper heating power. Thus the heat loss of the middle plane of upper capsule was reduced, leading to a smaller temperature difference between the capsule top and side walls. Also, the disturbance of heat conduction was increased due to increment of the temperature difference between the upper and lower cooling arms. Therefore the temperature at the bottom of the capsule was increased significantly and the temperature distribution was improved. But the flow field gathering at the top of the capsule have not yet been well suppressed so as the highest temperature there. Under these conditions, the highest and lowest temperatures of capsule surface were 19.6050K and 19.6049K respectively with the temperature uniformity of 0.1mk. So the ignition requirements for capsule surface temperature field can be approximately satisfied. As shown in figure 7.

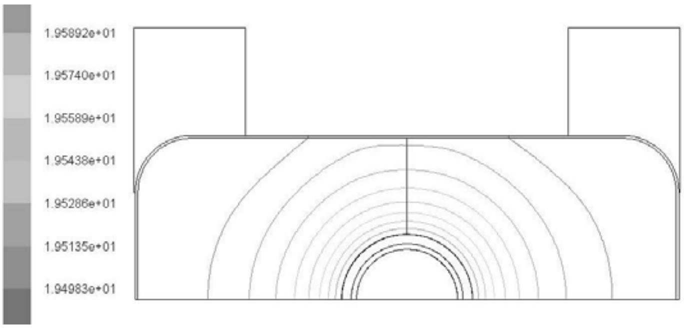

Figure 7. Temperature uniformity 0.1mK of the cryogenic target.

According to the calculation results, the separate control of auxiliary heating power of the hohlraum for the upper and lower parts and the temperature changes for the upper and lower cooling arms can maintain the temperature uniformity for capsule outer surface of 0.1mk, which meets the technical requirements of the system .

5. Conclusions

The effects of heat conduction and convection of NIF capsule temperature field was discussed by theoretical analysis and numerical simulation. The results show that auxiliary heating device should be arranged close to the mid-plane of hohlraum to supplement the heat losses caused by low thermal resistance, thereby satisfying the ignition requirements. There is an optimal heating power which can obtain a minimum temperature difference at the capsule surface. Also, the effects of free convection on temperature uniformity can be effectively suppressed by separate temperature controls of upper and lower cooling arms. Finally, the separate control of auxiliary heating power and independent temperature control of the upper and lower cooling arms can be integrated to maintain the temperature uniformity for capsule surface of 0.1mK, which meets the technical requirements of the system. Although there are a lot of simplification and assumptions in this paper, some good suggestions can still be provided to the temperature control for the cryogenic target system by our calculation results.

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