Numerical Investigation on The Temperature Control of a NIF Cryogenic Target

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Background

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. 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. Analytical calculations indicate that thermal gradient around the capsule should not exceed 0.1mK for these requirements.

Objectives

- Building a two-dimensional model for holhraum by FLUENT and studying the temperature distribution of capsule surface.
- Obtaining control method for the maximum temperature difference 0.1 mK of the capsule surface.

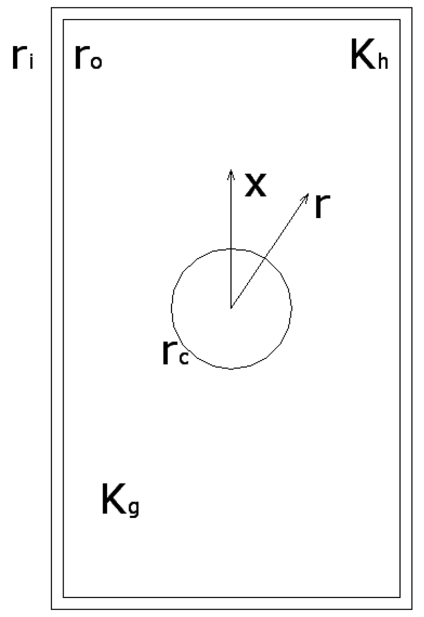
Conclusion

- Auxiliary heating device should be arranged close to the mid-plane of holhraum 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.
- The effects of free convection on temperature uniformity can be effectively suppressed by separate temperature controls of upper and lower cooling arms.
- 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

Theoretical Analysis

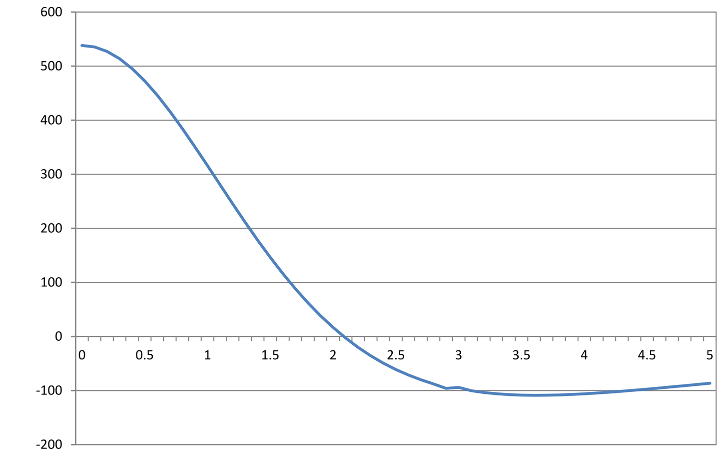
A simplified model of the holhraum was set up to determine the auxiliary heating power.

it is only necessary to study how to make the capsule in a uniform spherical temperature field.



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

Results



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.

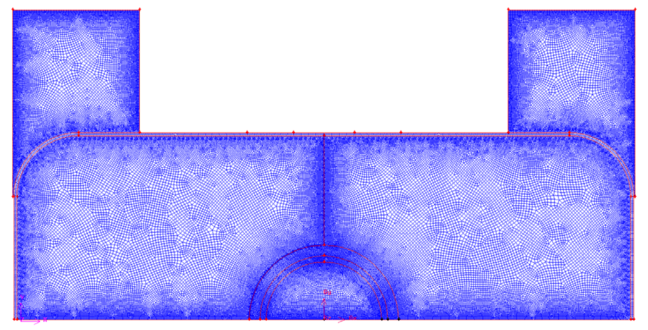
Numerical Investigation

Mesh

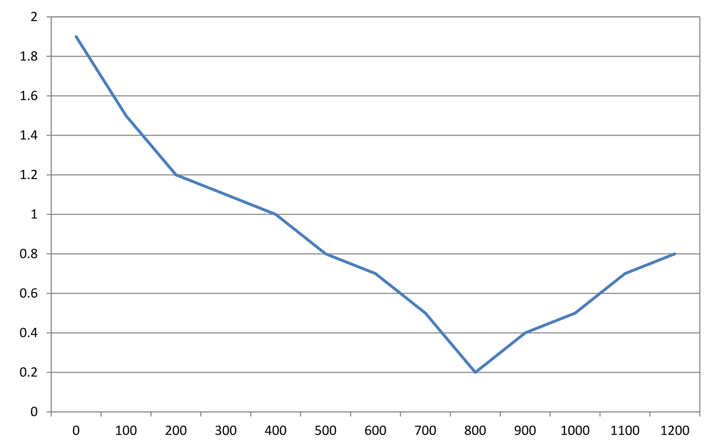
As the holhraum is a cylinder with axial symmetry properties, a two-dimensional model can be established and half of the structure was studied. meshes is 13,869.

Model meshes: 90,440

Capsule meshes: 13,869.



Auxiliary heating determination



The temperature difference at the surface of the capsule reduces by 2mk compared to the condition without auxiliary heating. When the heating power is less than 830mW/m², temperature difference at the surface of the capsule decreases with the increment of heating power. But when the heating power is greater than 830mW/m², the result is converse.

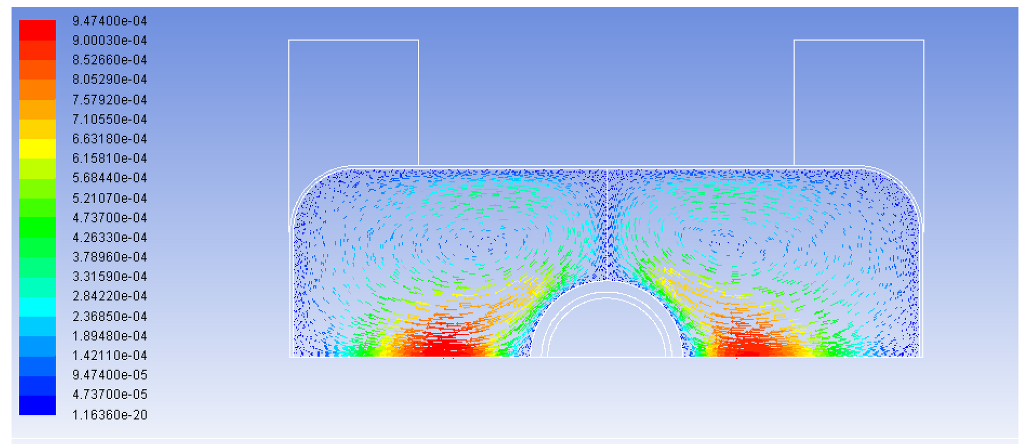
It can be concluded that there is an optimal heating power leading to the lowest temperature uniformity of 0.19 mK under other constant parameters.

Convection Depression

Velocity distribution

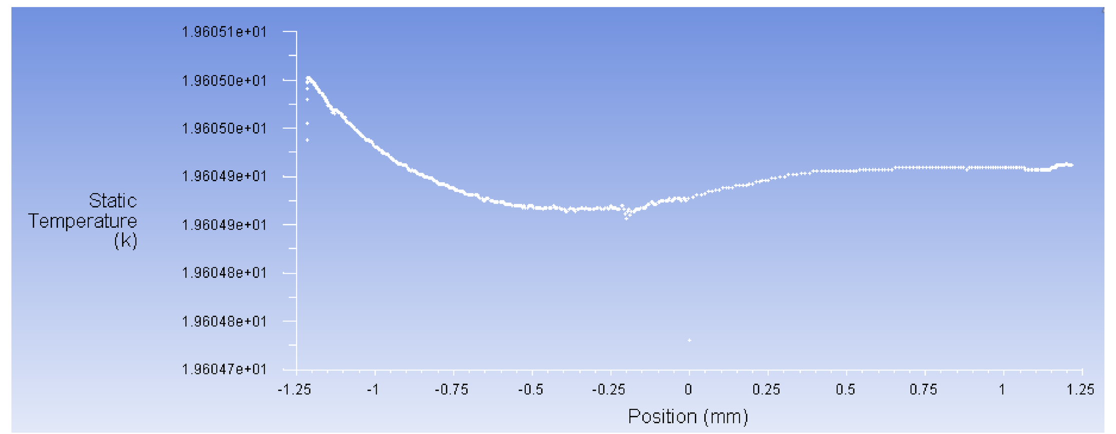
Free convection of hydrogen-helium gas happens under gravity in the holhraum, which has a significant impact on the capsule surface temperature distribution.

This can be reflected by the temperature distribution at the capsule surface(when the temperature of upper and lower arms are both 19.47k and the auxiliary heat flux in outer wall is 830 mW/m²). At this moment, the temperature at upper capsule is higher and has a temperature difference of about 0.4mk to the lowest surface temperature.



Independent cooling arm temperature

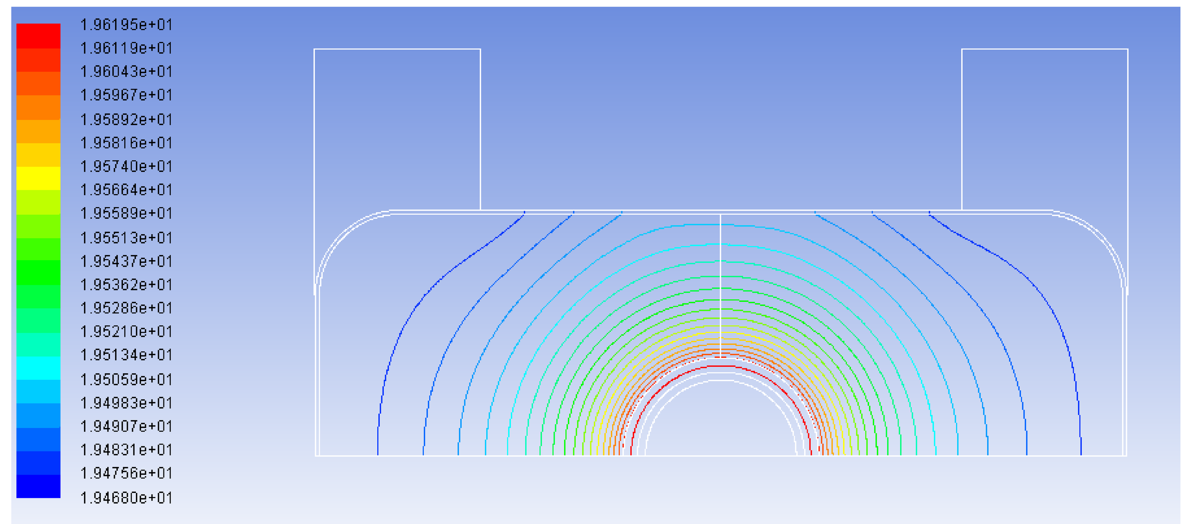
A heating was placed on the lower cooling ring to create a small thermal gradient on the cavity to protest gravity so as to suppress the development of free convection. By several calculations, the results show that temperature uniformity at the surface is best when the temperature difference between the upper and lower arms is 1mk.



Asymmetric Heating Controls

Temperature distribution

Symmetrical auxiliary heating and separate temperature controls of cooling arms are still not enough to satisfy the requirements of capsule surface temperature. Then the separate control of auxiliary heating power was analyzed. By repeated simulations, it's found that an auxiliary heating power of 950W/m² for the upper half with the upper arm temperature of 19.468k and 700W/ m² for the lower half with the lower arm temperature of 19.4707k are proper.



This is because the heat transfer temperature difference between upper holhraum walls and the capsule surface was weakened by the increment of the upper half heating power. Thus the heat loss of the middle plane of upper half 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 in such scheme and the highest temperature point was still at the top of the capsule. At this moment, the highest and lowest temperature of capsule surface were 19.6050k and 19.6049k respectively with the temperature uniformity of 0.1mk.

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