Design and Thermal Analysis of Temperature Control Experiment Box for Final Optic Assembly

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Abstract. The Final Optic Assembly (FOA) is one of the key components of the inertial confinement nuclear fusion device. The temperature change in the FOA is related to the laser frequency conversion efficiency of the frequency doubling crystal. In order to research the temperature control of FOA, this paper considers the internal atmosphere and internal structure of FOA, designed and fabricated a vacuum temperature control experiment box, and set up heat sources inside the box to simulate the internal heating of the FOA. This article uses different radiation heat transfer models to analysis the temperature field of the vacuum experiment box. Compare the thermal simulation results of the S2S model and the DO model, and compare them with the actual temperature of the vacuum experiment box under the same boundary conditions. The results show that the S2S model fits well with the experimental results and is more suitable for thermal analysis of FOA, which is of great significance to the follow-up FOA temperature control research.

Keywords: Final Optic Assembly, thermal analysis, S2S model, DO model.

1. Introduction
In recent years, Laser Inertial Confinement Fusion (LICF) has become the focus of more and more researchers. The Final Optic Assembly (FOA) is an important part of the laser inertial confinement nuclear fusion device. One of its main functions is to convert the frequency of the laser to convert the fundamental frequency light into the triple frequency light. This function is realized by the frequency doubling crystal installed in the FOA. The material of the frequency doubling crystal is potassium dihydrogen phosphate (KDP), and the temperature will have a great influence on the frequency doubling efficiency of the frequency doubling crystal [1, 2]. To sum up, the temperature is directly related to whether the terminal optical components can play its role.

Inside the FOA, the main factors that cause the temperature change of the frequency doubling crystal are the heat generated by the internal angle-adjusting motor during operation and the influence of the external environment on the inside of the FOA. It is worth noting that the interior of the FOA is a low vacuum environment, and its pressure is below 10kPa, so the main internal heat exchange method is radiation heat exchange. Therefore, finding a suitable radiation heat transfer model is of great significance for studying the temperature control of terminal optical components.
With the development of computer technology and finite element method, the commonly used radiation heat transfer models for radiation heat transfer include P-1 model, Rosseland model, DTRM model, S2S model, and DO model. The P-1 model and the Rosseland model are suitable for the optical depth > 1, and the DTRM model and the DO model are suitable for any optical depth. The DO model is more suitable when there is a local heat source inside. If the DTRM model is applied, it will consume CPU time very much. The S2S model is suitable for radiative heat transfer in a closed cavity without a radiant medium, and is suitable for simulation of radiant heat transfer in vacuum [3]. In summary, this article uses the DO model and the S2S model to analyze the temperature field of the vacuum temperature control test box, and compares the results obtained with the experimental results, and analyzes the advantages and disadvantages of the two methods.

2. Theoretical basis of numerical calculation of radiative heat transfer

Numerical Heat Transfer (NHT), also known as Computational Heat Transfer (CHT), refers to a field of heat transfer and heat transfer that describes the control equations of flow and heat transfer problems using numerical methods and is solved by computers. An interdisciplinary combination of numerical methods [4]. ANSYS FLUENT is the most successful solver for computational fluid dynamics (Computational Heat Dynamics, CFD) so far. It uses a finite volume method based on a completely unstructured grid and provides users with a variety of heat transfer models for various heat transfer states.

2.1. Surface to Surface model

Surface to Surface model (S2S) can calculate the radiative heat transfer between the dust-filled surfaces in the enclosed (area). The amount of radiant heat exchange between two surfaces depends on their size, spacing and direction. This characteristic can be measured by the geometric quantity of the observation coefficient (apparent coefficient). The main assumption of the S2S model is to ignore all radiation absorption, emission and scattering, so only the radiation heat transfer between surfaces is considered in the model.

Assuming that in a closed cavity composed of N diffuse dust surfaces, the temperature \( T_i \) of each surface is known. For the sake of simplicity, it is assumed that each surface is not concave, that is, \( X_{i,i} = 0, i = 1 \sim N \) and using the relativity of the angle coefficient \( A_i X_{j,i} = A_i X_{i,j} \), under this condition, for any surface \( i \) [5]:

\[
J_i = \varepsilon_i \sigma T_i^4 - (1 - \varepsilon_i) \sum_{j=1}^{N} J_j X_{i,j} i = 1,2,...,N
\]

Where \( J_i \) the effective radiation of any surface is \( i \), \( \varepsilon_i \) is the emissivity of the NO. \( i \) Surface element, \( \sigma \) is the Stefan-Boltzmann constant, \( X_{i,j} \) is the radiation angle coefficient from the NO. \( i \) Surface element to the NO. \( j \) Surface element, and if \( i = j \) then \( X_{i,j} = 0 \). \( N \) is the total number of surface elements participating in the radiation. The iterative method can be used to find the effective radiation \( J_i \) of each surface, and the effective radiation \( J_i \) of each surface can be calculated by putting it into equation (2) to calculate the radiation heat transfer \( q_{i,j} \) of each surface

\[
q_{i,j} = X_{i,j} (J_i - J_j)
\]

When the number of radiating surfaces is large, the calculation amount of the surface radiation model is very large. In order to reduce the calculation time and storage requirements, the number of radiating surfaces can be reduced by creating surface beams. The temperature \( T_{sc} \) of the surface beams is obtained by the area weighted average (3)
Where $A_f, T_f$ are the area and temperature of the surface $f$ respectively, and the summation is performed on all the surfaces that make up the surface bundle.

### 2.2. Discrete Ordinates (DO) model

The Discrete Ordinates (DO) model solves the radiation propagation equation from a finite solid angle. Each solid angle corresponds to the fixed direction $\hat{s}$ in the coordinate system (Descartes). The discrete accuracy of the solid angle is determined by the user. DO model converts the equations into light-radiation transport equations in the space coordinate system, and solves as many transport equations (radiation intensity) as there are as many solid angle directions. The method of solving the equation is the same as that of the fluid flow and energy equation.

For a medium with absorption, emission, and scattering properties, the radiative transfer equation (RTE) at position $\vec{r}$ and along direction $\hat{s}$ is:

$$
\frac{dI(\vec{r}, \hat{s})}{ds} + (a + \sigma_s)I(\vec{r}, \hat{s}) = an^2 \frac{\alpha T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\vec{r}, \hat{s}')\Phi(\vec{r}, \hat{s}')d\Omega
$$

Where $\vec{r}$ is the position vector, $\hat{s}$ is the direction vector, $s$ is the travel length along the way, $a$ is the absorption coefficient, $n$ is the refraction coefficient, $\sigma_s$ is the scattering coefficient, $\alpha$ is the Stefan-Boltzmann constant, $I$ is the radiation intensity, $T$ is the local temperature, $\Phi$ is the phase function, $\Omega$ is The solid angle in space, $(a + \sigma_s)s$ is the optical depth of the medium.

The DO model regards the radiative transfer equation (RTE) along $\hat{s}$ as a certain field equation, and FLUENT allows the gray band model to be used to simulate non-gray body radiation. For the spectral intensity $I_\lambda(\vec{r}, \hat{s})$, the radiation transfer equation is:

$$
\nabla \cdot (I_\lambda(\vec{r}, \hat{s})\hat{s}) + (a_\lambda + \sigma_s)I_\lambda(\vec{r}, \hat{s}) = a_\lambda n^2 I_{\lambda b} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I_\lambda(\vec{r}, \hat{s}')\Phi(\vec{r}, \hat{s}')d\Omega
$$

Where $\lambda$ is the radiation wavelength, $a_\lambda$ is the spectral absorption coefficient, and $I_{\lambda b}$ is the blackbody radiation intensity determined by PLANCK’s law. It is assumed that the scattering coefficient, scattering phase function and refraction coefficient are independent of wavelength.

### 3. Design of vacuum temperature control experiment box

Due to the large size of the Final Optic Assembly (FOA) and its complex internal structure including many precision instruments and optical components, it is difficult to directly conduct temperature control experimental research on FOA. Therefore, this paper designs and makes a vacuum temperature control experiment box to conduct temperature control experimental research on FOA.

The internal atmosphere of FOA is low vacuum (below 10kPa). There are three angle-adjusting motors inside the FOA near the frequency doubling crystal. When the angle-adjusting motors work, they will generate heat and become a factor that affects the internal temperature field of the FOA. The difference in the distribution of the heat source will also have a great impact on the internal temperature field of the FOA.

In summary, the temperature-controlled experiment box must meet the following requirements: keep a low vacuum inside the box and keep the air pressure below 10kPa; the size of the experiment box is scaled down according to the size of the FOA, and the relative positions of the internal structures are roughly the same as the FOA; A heating rod is set in the experiment box to replace the heating of the
motor to simulate the internal heat source; a vacuum socket is set to supply power for the internal heat source, and the temperature information collected by the PT100 temperature sensor is transmitted to the temperature collector. The temperature control experiment box and related equipment is shown in Figure 1.

![Temperature control experiment box and related equipment.](image)

**Figure 1.** Temperature control experiment box and related equipment.

Since the ultimate pressure of the vacuum pump is at least one order of magnitude lower than the ultimate pressure required by the vacuum chamber, a single-stage direct-coupled rotary vane vacuum pump with a rated pumping speed of 25 and an ultimate pressure of 200Pa can be used to pump the internal pressure of the experiment box to -99.32 kPa.

In summary, the vacuum temperature control experiment box can simulate the conditions that affect the temperature field inside the FOA, and can be used for FOA temperature control research.

### 4. Temperature field simulation

#### 4.1. Experiment box model and meshing

Import the experimental box model into the finite element software ANSYS as shown in Figure 2(a), and use the by caps in the fill function to extract the fluid domain in the internal space. Use the software's own meshing function to mesh the solid domain and fluid domain separately, and refine the mesh at the internal heat source to improve the accuracy of meshing. The available mesh is shown in Figure 2(b).

![Experiment box model and mesh.](image)

**Figure 2.** (a) Experiment box model. (b) Mesh.
4.2. Material parameters and boundary condition settings
The finite element analysis in this article involves the calculation of temperature, so the density, specific heat capacity, thermal conductivity, and emissivity of solid materials are required. As shown in Table 1.

| Material type    | Density (kg/m$^3$) | Specific heat capacity (J/(kg·K)) | Thermal conductivity (W/(m·K)) | Emissivity |
|------------------|--------------------|-----------------------------------|-------------------------------|------------|
| Polycarbonate    | 1200               | 1170                              | 0.24                          | 0.94       |
| Plexiglass       | 1180               | 1424                              | 0.19                          | 0.94       |
| Aluminum         | 2660               | 871                               | 162                           | 0.04       |

Since the object of this study does not exchange gas with the outside, the inside is set as an incompressible ideal gas, and because the inside of the experiment box is in a low vacuum environment, the working environment is set at 10kPa.

Through calculation, the power of the internal heat source is 2W (171379.6W/m$^3$), 2W, 4W (141143W/m$^3$). Since the experiment box is placed in the laboratory, the temperature boundary condition of the outer wall of the box is 26℃, and its convective heat transfer coefficient is set to 5W/(m$^2$·K).

4.3. Mesh independence check
In order to avoid the influence of the number of meshes on the calculation results, it is necessary to check the mesh independence. On the basis of the original mesh, the mesh is refined and updated, and the S2S model is used to calculate the maximum temperature in the box until the difference between the two simulation results before and after is within 2%. As shown in Table 2.

| Total number of meshes | 904130 | 1704245 | 3790063 | 6213017 |
|-----------------------|--------|---------|---------|---------|
| Number of fluid meshes | 508821 | 982367  | 2299674 | 3930408 |
| Maximum temperature   | 349.436K | 356.293K | 356.203K | 356.113K |

The greater the number of meshes the higher the calculation accuracy, but the greater the computer resources consumed. Therefore, under the condition of ensuring the calculation accuracy, reducing the number of meshes as much as possible is beneficial to save computer resources. Therefore, in the calculations in this article, the total number of meshes is 3790063, the number of nodes is 654416, the number of fluid domain meshes is 2299674, and the number of nodes is 414014.

4.4. Simulation results
In ANSYS FLUENT, the S2S radiation model and the DO radiation model are used to perform calculations. Because there is still a certain amount of air in the vacuum experiment box, there will be a certain amount of natural convection heat transfer in the box [6, 7], so turn on the Standard k-ε equation turbulence model. The calculation results are represented by the temperature contour diagrams of the two sections of the box, and the sections are shown in Figure3.
The temperature distribution results calculated by the S2S radiation model are shown in Figure 4. The calculated temperature in the box is 356.203K. It can be seen from the figure that there is not only radiation heat exchange inside the box, but also natural convection heat transfer. The gas with higher temperature inside the box accumulates in the upper part of the box, making the temperature of the upper part of the box higher than the temperature of the lower part.

**Figure 3.** Box section view.

**Figure 4.** Temperature contour diagram of S2S radiation model.
The temperature distribution result calculated by the DO radiation model is shown in Figure 5. The temperature within the box is calculated to be 356.090K. Compared with the 356.203K obtained by the S2S radiation model, it is found that the temperature distributions obtained by the two radiation models are roughly the same. From the calculation time point of view, the DO model consumes longer time than the S2S model.

![Figure 5. Temperature contour diagram of DO radiation model.](image)

In summary, both the DO model and the S2S model can simulate the temperature field inside the vacuum experiment box.

5. Experiment
Three PT100 sensors are installed inside the experiment box. The installation position of the PT100 sensors is shown in Figure 6. Sensors 1, 2, and 3 are respectively installed on 3 internal analog heat sources to measure the temperature of the heat source inside the box; sensor 4 is used to measure the external temperature of the box; the sensor 5 is installed inside the box and is used to measure the air temperature near the wall inside the box. The temperature measured by the 5 sensors is read out by an external thermometer. Compare the actual temperature inside the box with the temperature of the corresponding position in the simulation result to verify the accuracy of the temperature field obtained by the simulation.

![Figure 6. Sensor distribution map.](image)
The temperature change curve obtained through the experiment is shown in Figure 7. 0-720s is the temperature at which the vacuum experiment box is not working, and the temperature obtained by the 5 sensors is basically the same. 720s-3600s is to turn on the DC power supply to make the heating rod inside the simulated heat source generate heat and stabilize the internal temperature. The final pressure value is 0.30kPa. 3600s-3740s, turn on the vacuum pump to evacuate the interior. During the evacuation process, the internal temperature will drop. When the pressure is -91.32kPa, stop the vacuum pump. The internal heat source continued to heat the internal environment during 3740-11000s, and finally tended to a stable state.

![Temperature curve](image)

**Figure 7.** Temperature curve.

The comparison between the actual temperature values measured at each point in the steady state and the temperature values obtained through the S2S model and the DO model simulation is shown in Table 3.

| Sensor       | Sensor1   | Sensor2   | Sensor3   | Sensor5   |
|--------------|-----------|-----------|-----------|-----------|
| Actual stable temperature | 354.81K   | 355.56K   | 355.30K   | 308.06K   |
| S2S model simulation stable temperature | 353.762K  | 355.664K  | 355.119K  | 309.709K  |
| DO model simulates stable temperature | 351.479K  | 353.497K  | 355.077K  | 309.396K  |

It can be seen from Table 3: For the S2S model, the difference between the simulated value and the experimental value is 1.048K, 0.104K, 0.181K, and 1.649K. For the DO model, the difference between the simulated value and the experimental value is 3.331K, 2.063K, 0.23K, and 1.336K. In summary, the simulation results obtained by the S2S model are more practical, and the S2S model is more suitable for the temperature simulation of the vacuum experiment box than DO model.
6. Conclusion
In this paper, based on the conditions that have a significant influence on the temperature inside the FOA, this paper designs and manufactures a vacuum box that can be used to simulate the temperature field inside the FOA. In addition, the heat transfer model of the vacuum box is established, and the temperature simulation of the vacuum box is performed using the two radiation models, the DO model and the S2S model, respectively. The actual temperature of 5 temperature measurement points is obtained by experiment with the built vacuum box, and the actual temperature is compared with the simulation result, and the following conclusions are drawn:

The internal structure of the vacuum experiment box is similar to the inside of the FOA, which can stably provide a heat source, and can maintain the vacuum degree below 10kPa, which can well simulate the internal temperature field of the terminal optical component.

The experiment shows that the air pressure inside the box has a great influence on the temperature inside the box. The main reason is that the air inside the box becomes thinner during the vacuuming process, which greatly reduces the convective heat transfer coefficient of each part of the interior. Only when it continues to rise under stable conditions can heat radiation become the main factor affecting the internal temperature.

By comparing the simulated temperature and the experimental temperature, it can be seen that the S2S model is more suitable for the temperature field simulation of the vacuum experiment box than DO model. And the S2S model saves more computer resources.

References
[1] Liang Y, Su R, Lu L, et al. Temperature Nonuniformity Occurring During the Cooling Process of a KDP Crystal and its Effects on Second-Harmonic Generation, J. Applied Optics, 2014, 53(23): 5109-5116.
[2] Li W, Feng G, Han X, et al. High-Intensity Laser Frequency Doubling in KDP with a Temperature Distribution, C. IEEE, 2010.
[3] Zhongzhe Duan, ANSYS FLUENT fluid analysis and engineering examples, M. Publishing House of Electronics Industry. Beijing, 2015, pp. 157-221.
[4] Wenquan Tao, Numerical Heat Transfer (Second Edition), M. Xi’an Jiaotong University Press. Xi’an, 2002, pp.1-26.
[5] Wenquan Tao, Heat Transfer (Fifth Edition), M. Higher Education Press. Beijing, 2019, pp.402-406.
[6] Hui Lin, Experimental and Simulation Study on Natural Convection on horizontal pipe at low remperation and pressure, D. Shanghai: Shanghai Jiaotong University, 2019, pp.31-87.
[7] Li Ding, Qie D F. Experiment on Surface Natural Convection Heat Transfer of Vertical Plate under Different PDressures, J. Acta Aeronautica et Astronautica Sinica, 2016, 37(5):1506-1511.