Thermal Analysis of Main Components in The Design of High-power Tetrode

Haoran ZHONG¹, Wenbo CHEN¹*, Xueyu GONG¹, Honghu WU², Puqiong YANG¹, Yongjie LUO¹

¹ School of Electrical Engineering, University of South China, Hengyang, Hunan, 421001, China
²Chengdu Xuguang Electronic Co. Ltd, Chengdu, Sichuan, 610500, China
*Corresponding author’s e-mail: afwind3@gmail.com

Abstract. High-power tetrode is a key component in ion cyclotron resonance heating system, as the final amplifier component to increase the RF power to the megawatt level. Thermal analysis is of important significance to the development and use of high-power tetrodes. In this paper, the trajectory of particles during the operation of the tetrode is obtained by CST particles studio, and its energy conversion is analyzed through the simulation results. Then the grid, anode, and support structure of the tetrode are analyzed thermally in Ansys Workbench, and the results are helpful to the design of the heat dissipation structure of the tetrode.

1. Introduction

1.1. Research background
Ion cyclotron resonance heating is a commonly used auxiliary heating method in controlled nuclear fusion. As the final amplifier component, the high-power tetrode is an important component in the ion cyclotron resonance heating system, to amplify the radio frequency signal transmitted from the front pole to the megawatt level, and finally inject microwave energy into the plasma of EAST(Experimental and Advanced Superconducting Tokamak)[1]. Thermal analysis is of great significance to the design and improvement of high-power tetrodes. While the tetrode is working, the hot cathode will continue to radiate heat to the internal structure of the tube, the heat accumulation in the tube will cause thermal deformation of the tetrode structure, affect the stability and service life of the tetrode, and even cause irreversible physical damage. It is very important to optimize the design of a good heat dissipation structure for making a tetrode with higher operating frequency and higher output power. Therefore, it is necessary to conduct thermal analysis on the high-power tetrode.

At present, there are relatively few researches on thermal analysis of tetrodes. Yaqi Zhao’s research simplifies the tetrodes into four simple plates whose grid is composed of tungsten and copper. The temperature distribution of the four plates is analyzed [2]. The influence of the tetrode support structure and anode on temperature is not considered. In another study, they analyzed the relationship between particle motion and radiation in the tube, and verified that the temperature radiation trend is consistent with the direction of particle motion [3]. The effect of particle heat loss on the temperature in the tube is not analyzed.

This article will analyze a simplified model of a typical tetrode provided by Chengdu Xuguang Electronics Co. Ltd. First introduce its structure and analyze the significance of each part in the design
of its heat dissipation. Introduce its working principle and the corresponding heat transfer principle. Analyze the effect of the support structure and anode on the heat dissipation of the tetrode in the simulation. Considering that the electron flow of the tetrode has a certain effect on the temperature of the tetrode when it is working, the movement state of the electrons in the tetrode will be further analyzed, and then simulated by CST particle studio and Ansys Workbench.

1.2 The tetrode structure
The main components of the tetrode are cathode, anode, control grid, screen grid, and the support structure. Figure 1 shows the structure of the tetrode model.

![Figure 1. The tetrode simplify model](image)

The material of the cathode is tungsten. When the cathode is heated to 2200K, the cathode will generate a very large emission current. Its emission current density is 0.7~1.5 $A/cm^2$. The cathode is the component that generates the most heat in the entire tetrode. Due to the vacuum environment in the tube, the heat generated by the cathode will only be transferred to other components through heat radiation and heat conduction.

Both the control grid and screen grid use pyrolytic graphite as the material and are made after deposition and photolithography. The grid made of pyrolytic graphite not only has good electrical and thermal properties, but the thermal conductivity parallel to the deposition surface is similar to that of copper. And it has good radiation characteristics (80% of the ideal black body), so its heat can be effectively dissipated through radiation and heat conduction. Since the grid determines the performance of the tetrode to a large extent, it is necessary to focus on its heat dissipation capacity and thermal deformation.

The anode is not only a collector of electrons, but also a part of the tetrode shell, Heat dissipation is another important task of the anode. The temperature of the anode will affect the temperature of the grid in the form of thermal radiation, and it will also affect the stability of the tetrode due to thermal deformation. In several cases, it will directly affect the working life of the tetrode. A part of the focus of thermal analysis is to analyze the anode temperature to further design more optimized heat dissipation methods. The anode cooling method usually has four methods: natural cooling, forced air cooling, forced water cooling, and evaporative cooling.

2. Particle Simulation

2.1. The Theory of Particle Simulation
The movement of electrons will affect the temperature distribution of the tetrode. The tetrode emits electrons by heating the cathode. The electrons emitted from the cathode will accelerate under the action of the electric field, and finally hit the anode according to a certain trajectory. The electrons are in the electric field. A certain amount of kinetic energy is obtained under the action of the force. When it hits the inner surface of the anode, the kinetic energy is converted to the anode in the form of heat energy, which increases the temperature of the anode [4]. The energy conversion of the tetrode can be expressed:

$$P_{in} = P_T + P_{out}.$$  

In static working conditions, the kinetic energy of electrons under the acceleration of the anode voltage is equal to the work done when the electric field force pulls the electrons from the cathode to

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the anode:

\[ E_k = \frac{1}{2} m v^2 = eE_a \]

Where \( m \) is the electron mass, \( v \) is the speed at which the electron reaches the anode, \( e \) is the electron charge, and \( E_a \) is the anode voltage.

Suppose the electron beam reaching the anode is \( n \). \( I_a \) is anode current.

\[ I_a = ne \]

then \( I_a \) is the total energy \( W \) converted into heat.

\[ W = neE_a \]

2.2. Result of Particle Trajectory

The outer surface of the cathode is set as the particle emission surface, and the electron emission density is 1.2A/cm². In order to simulate the real thermionic emission, set the thermionic emission with an initial temperature of 2200K, set the potential distribution of each pole, and perform particle trajectory simulation after completing the preceding steps, The simulation results are shown in Figure 2.

It can be seen from the particle trajectory that in an ideal state, when control grid's voltage is negative, its intercepted current is zero. Changing the control grid voltage can control the density of particles passing through. In the design of the tetrode, in order to allow more electrons to pass through the grid, the grid design adopts the Correspond-grid structure, which the grid lines of the control grid and the screen grid are aligned. The electric field of the control grid will converge the electrons emitted from the cathode to form an electron beam. Therefore, in theory, the screen will not intercept the electrons. The electron beam will pass between the grid wires of the screen and move toward the anode.

In general, the current of the tetrode is controlled by control grid voltage, and screen grid voltage and the anode voltage determine the energy of the electrons to the anode. The post-processing of CST particle studio can obtain the total heat loss of electrons, which is similar to the heat loss \( Q \) on the inner surface of the anode under ideal conditions. In the thermal analysis, \( Q \) will be converted into heat flux, which is applied to the inner surface of the anode as a thermal boundary condition.
3. Thermal Analysis

3.1. The Theory of Thermal Transfer

There are three ways of heat transfer: heat conduction, heat convection, and heat radiation. The inside of the tetrode is a vacuum environment, and the heat transfer is mainly divided into two ways: heat conduction and heat radiation. Thermal conduction means that due to the temperature difference between two objects in contact, the temperature will be transferred from a high temperature to a low temperature. Expressed by the Fourier formula:

\[ \frac{KA(T_{hot} - T_{cold})}{d} = \frac{Q}{t} \]

where \( K \) is thermal Conductivity, \( A \) is object contact surface area, \( Q \) is the heat transferred in time \( t \). The heat \( Q \) radiated from plane \( i \) to plane \( j \) be expressed as:

\[ Q = \sigma \varepsilon F_{ij} A_i (T_i^4 - T_j^4) \]

where \( Q \) is Heat flux, \( \sigma \) is Boltzmann constant, \( \varepsilon \) is Emissivity, \( A_i \) is the area of radiating surface \( i \), \( F_{ij} \) is angle coefficient of surface \( i \) and \( j \).

For heat conduction, it follows the governing equations for thermal analysis:

\[ q + \frac{\partial}{\partial x} \left( k_{xx} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_{yy} \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_{zz} \frac{\partial T}{\partial z} \right) = \rho c \frac{dT}{dt} \]

and

\[ \frac{dT}{dt} = V_x \frac{\partial T}{\partial x} + V_y \frac{\partial T}{\partial y} + V_z \frac{\partial T}{\partial z} + \frac{\partial T}{\partial t} \]

where \( V_x, V_y, V_z \) represents the medium conduction rate [5].

3.2. The Result of Thermal Analysis

Table 1. are main materials’ parameter. Since pyrolytic graphite is an anisotropic material.

| Materials’ parameters            | Main Materials | Tungsten | Copper | Pyrolytic Graphite |
|----------------------------------|----------------|----------|--------|-------------------|
| Coefficient of thermal expansion (10^{-6} /°C ) | 4.6            | 5.2      | 0.7    | 22                |
| coefficient of thermal conductivity (W/m·k)   | 174            | 340      | 382    | 2.8               |
| Poisson’s Ratio                   | 0.28           | 0.3      | 0.25   | 0.45              |
| Young’s modulus (GPa)             | 411            | 200      | 28     | 13                |

Simulate two structure models separately. the ambient temperature is normal, the cathode is used as the heat source. The outer surface of the cathode and the inner surface of control grid, the outer surface of control grid and the inner surface of the screen, the outer surface of the screen and the inner surface of anode, are four sets of radiation pairs [6]. The heat loss caused by particle bombardment is applied to the inner surface of the anode in the form of heat flux with a size of 0.015W/mm².

Figure 5. are temperature distribution without supporting structure after hiding the maximum temperature of cathode:1926°C. In the figure, the control grid has a maximum temperature of 1253.2°C, the temperature of the screen grid is evenly distributed at 555°C, and the overall temperature of the anode is approximately 554°C.
Figure 3. (a) Temperature distribution without supporting structure (b) Control grid (c) Screen grid

Figure 6. are temperature distribution with supporting structure. The highest temperature is also 1158.7°C in the control grid. However, the lowest temperature of the control grid is much lower than unsupported one. because the temperature is transferred to the supporting structure through heat
conduction and diffuses out. The anode temperature is much higher than the former. Therefore, the temperature of the screen is also more balanced. As a part of the heat dissipation structure, anode can bear as much temperature as possible, so that the temperature in the tube can be released through heat dissipation measures. It can be seen that adding a support structure to the thermal analysis can not only make the results more accurate, but also provide more ideas for heat dissipation design.

Figure 4. (a) Temperature distribution with supporting structure (b) Control grid (c) screen grid
4. Conclusion
The main purpose of this article is to provide thermal analysis simulation data for high-power tetrode design. Therefore, the main components of the high-power tetrode are analyzed. Using the CST particle studio to simulate the particle trajectory to obtain the heat loss of the particle during the movement. Then set the boundary conditions in Ansys Workbench to get the temperature distribution of tetrode, which conforms to the actual situation. The importance of the support structure and anode to the heat dissipation of the tetrode is analyzed, which provides a basis for the heat dissipation design in the design process of the high-power tetrode.

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