# Thermal design of double helium gap conduction test facility

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**Abstract**. In order to obtain the heat transfer characteristics of the helium gap in conditions of different thickness and linear power in high temperature range, on the basis of previous research, the original test device was improved. Through the theoretical design of double helium, the test device can perform experiments under high temperature conditions. Compared with the experimental results, the theoretical design values are in good agreement with the experimental results. According to the design results of the test device, the helium gap test can be carried out in a high temperature range, and the test results can provide reference for the design of the material irradiation assembly.

**Key Words**: helium gap; heat conduction; radiation assembly.

## 1 Introduction

China Experiment Fast Reactor (CEFR) is the first fast reactor in China, which the maximum neutron flux rate is $3.7\times10^{15}cm^{-2}\cdot s^{-1}$. The CEFR can be used as an advanced neutron irradiation platform to carry out a variety of core materials and fuel irradiation test, which provide strong technical support for the reactor materials and fuel R&D. The key issue in establishing the fast reactor irradiation technology is to design and develop the irradiation device to meet the requirements of various irradiation tasks. There are many types of irradiation devices while CEFR relies mainly on R&D of in-line irradiation devices that can be placed directly into the core to carry out irradiation test of structural materials and fuels[1].

In order to make the design of the radiation assembly more accurate, the thermal calculation of the irradiation assembly is firstly carried out, and the similar experimental device was built to validate the calculation. Ma Yong-zhe [2-3] et al have done a research on the heat transfer experiment of the material irradiation device at low temperature, but the device cannot meet the requirements of the irradiation condition[4] of material under high temperature. The scheme presented in this paper[4] is provided with double helium gap according to the structure design of the irradiation device, to ensure the linear power of experimental device can reach the level of the irradiated samples. The temperature of test device was measured by thermocouple and the industrial computer was used to collect and store the experimental data. The difference between experimental data and theoretical calculation was analyzed after the experiment.

## 2 Test device

The figure of double helium gap conduction test facility[5] was shown in Figure 1. The experimental device includes a gap heat transfer device, a test bench, a vacuum system, a coolant water circuit, an electric control system and other equipment. The vacuum system is used to vacuum air and pump helium for the gap heat transfer device, which mainly comprises a vacuum mechanical pump, a helium bottle and a pressure gauge. The coolant water circuit is used for taking away the heat of the gap heat transfer device and keeping temperature stable. Electrical control system is responsible for controlling the electrical control and monitoring temperature, and has a temperature warning function to alarm the ultra-high temperature for the protection of test personnel and equipment safety.

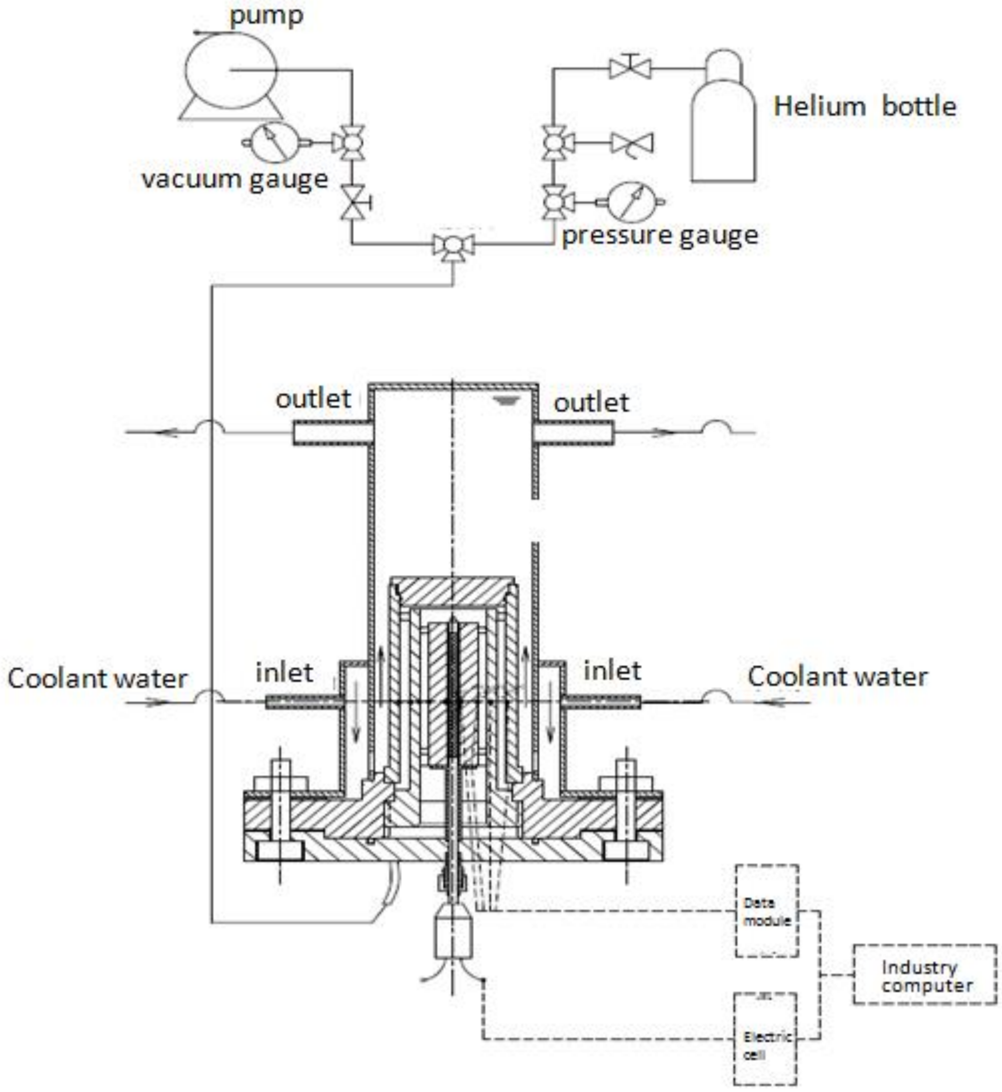

FIG. 1. The scheme of Experimental device

The main body of the gap heat transfer device is composed of an electric heating element, a three-layer heat transfer sleeve, a mounting flange, a supporting base and a water circuit sleeve. The structure of the device is shown in Fig 2. There are two-layer helium gap among three-layer sleeves. The innermost heat transfer sleeve is made of pure copper, the other two layers are austenitic stainless steel. The inner and middle sleeves can be replaced in order to carry out helium transfer test under different conditions. The specific parameters of the sleeve in this test are shown in Table 1. The inner and outer sides of the copper inner sleeve, the middle sleeve and the outer sleeve are slotted symmetrically, and eight armored thermocouples are inserted to monitor the helium gap temperature. The measurement range of the thermocouple is 0 to 800 ℃. The overall size of the gap heat transfer device is Φ190× 610mm, which is sealed mainly by the bearing seat and the mounting flange of the O-ring and sealant seal. The helium pressure is 0.1MPa(at room temperature) and the maximum pressure of not more than 0.3 MPa. The highest heating power of the rod is 3.04kW while the maximum the line power density is 19kW/m. The maximum temperature of heat component is designed to not exceed 800℃. The flow rate of cooling water in the heating section is 0.4 ~ 0.6m / s, and the inlet cooling water temperature is about 20℃.

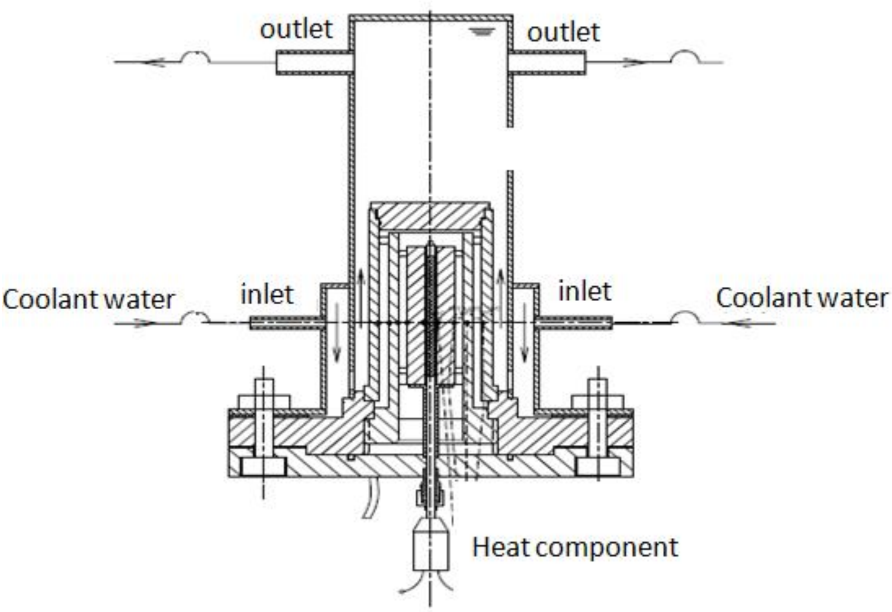

*FIG. 2. Helium heat transfer device*

## 3 Thermal design

### 3.1 Introduction to the experimental model

Schematic diagram of the test device [6] is shown in Figure 3. The middle region is a cylindrical heating element. From outside to inside, followed by the ring of stainless steel, helium, stainless steel, helium, copper. The geometric dimensions and temperature label of the layers shown in the figure 3, where, the temperature of site $d_0$ ~ $d_5$ were $t_0$ ~ $t_5$.Water cooling circuit set in the outermost layer of stainless steel to take away heat of the test device.

In the experimental device, the outermost helium gap ($d_4$ ~ $d_3$) was used to control the temperature to reach the experimental conditions. The helium gap ($d_2$ ~ $d_1$) of the intermediate layer was the area of interest. In order to make sure that the test was carried out under the similar conditions of irradiation cans in the reactor, the inner layer of the helium gap is set as pure copper while the outer layer of that is set as stainless steel.

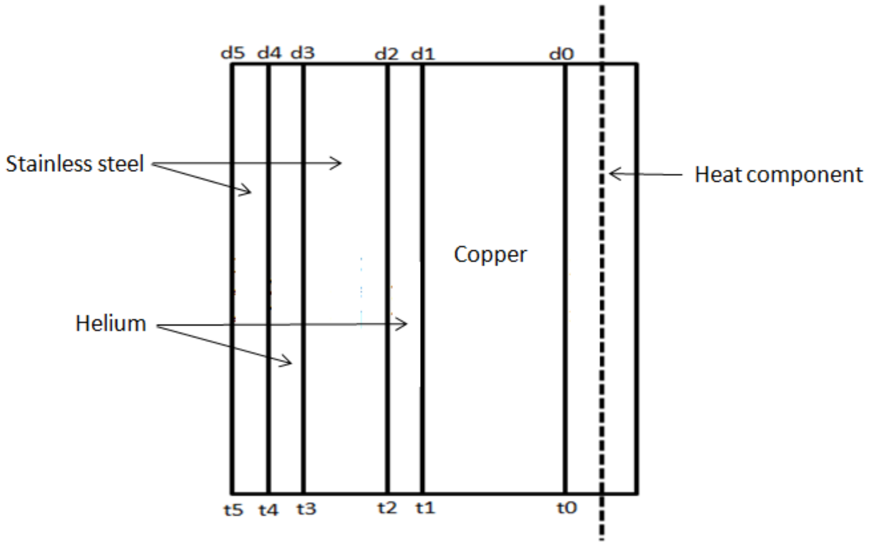

*FIG. 3. Schematic diagram of the test section*

### 3.2 Theoretical model

1) Helium gap temperature calculation

For a double helium gap, heat transfer consists mainly of radiation heat transfer and conduction. They are calculated as follows:

$$\phi_{\mathrm{radiation}} = \frac{5.67\mathrm{A}_i}{\dfrac{1}{\varepsilon_i} + \dfrac{A_i}{A_s}\left(\dfrac{1}{\varepsilon_s} - 1\right)} \times \left[\left(\frac{T_i}{100}\right)^4 - \left(\frac{T_s}{100}\right)^4\right] \quad (1)$$

Where $\varepsilon_i$ is the emissivity of inter surface; $\varepsilon_s$ is the emissivity of outer surface; $A_i$ is the inter surface area, $\mathrm{m}^2$ ; $A_s$ is the outer surface area, $\mathrm{m}^2$ ; $T_i$ is the helium gap inter surface temperature, K; $T_s$ is the helium gap outer surface temperature, K.

$$\phi_{\mathrm{conduction}} = \frac{2\pi k_{He} l}{\ln\left(\dfrac{d_s}{d_i}\right)} \times (\mathrm{T}_i - \mathrm{T}_s) \quad (2)$$

Where $k_{He}$ is the thermal conductivity of helium, W/(m•K); $d_i$ is the internal diameter of the helium gap, m; $d_s$ is the outer diameter of the helium gap, m; $l$ is the axial length of helium gap, m.

The total heat release of the radiation container is:

$$\phi_{\mathrm{total\ heat}} = \phi_{\mathrm{radiation}} + \phi_{\mathrm{conduction}} \quad (3)$$

2) Calculation of external cooling of the test section

$$Nu_f = 0.012(\mathrm{Re}_f^{\,0.87} - 280)\,\mathrm{Pr}_f^{\,0.4}\left[1 + \left(\frac{d}{l}\right)^{2/3}\right]\left(\frac{\mathrm{Pr}_f}{\mathrm{Pr}_w}\right)^{0.11} \quad (4)$$

Applicable conditions:

$$1.5 < \mathrm{Pr}_f < 500 \qquad 0.05 < \frac{\mathrm{Pr}_f}{\mathrm{Pr}_w} < 20 \qquad 2300 < \mathrm{Re}_f < 10^6$$

### 3.3 Model design parameters

The designed helium gap thickness of CEFR structural material irradiation device[6] is shown in TABLE I. At the same time the outer diameter (inner wall of stainless steel) and inner diameter (outer wall of stainless steel) of the helium gap should be adjust to meet the temperature requirements.

TABLE I: DESIGN INPUT

| test | temperature of outer stainless steel wall（℃） | temperature of inner stainless steel wall（℃） | line power density（kW/m） | thickness of Helium gap（mm） |
|---|---|---|---|---|
| 600 | 463.0 | 630.8 | 19.046 | 0.5 |

A thicker gap (between $d_4$ and $d_3$) is set on the outside of the test gap to make sure the temperature of inner helium gap reach the test conditions under water cooling. The test will start when the temperature of the outer helium gap reach the design value.

The physical properties of the materials involved in the theoretical calculations in the test are shown in Table II.

TABLE II: PROPERTIES OF MATERIALS

| | Stainless steel | Copper |
|---|---|---|
| Thermal conductivity, W/（m·℃） | $k = 14.33 + 0.01309t$ | $k = 398$ |
| Expansion coefficient, /℃ | $\alpha = 1.58\times10^{-5} + 3.54\times10^{-10}\ t$ | $\alpha = 1.77\times10^{-5}$ |
| Emissivity | $\varepsilon$=0.35 | $\varepsilon$=0.22 |

Note: t is the temperature, ℃.

The thermal conductivity of the helium is as follows:

$$k = 0.1448\left(1+\frac{t}{273.15}\right)^{0.68}\left[1+\frac{1.665\times10^{-4}\left(\frac{p}{10^5}\right)^{1.17}}{\left(1+\frac{t}{273.15}\right)^{1.85}}\right] \qquad (5)$$

The geometric parameters of the test conditions are given in TABLE III [4] according to the structural design of the irradiating device .The data in TABLE III correspond to the case where the temperature rise of the cooling water is 1 °C while the temperature rise is 1.6 ° C when d3 increase 0.2 mm.

TABLE III GEOMETRIC PARAMETERS OF THE TEST CONDITIONS(mm)

|  | Gap thickness | $d_5$ | $d_4$ | $d_3$ | $d_2$ | $d_1$ | $d_0$ |
|---|---|---|---|---|---|---|---|
| TEST | 0.5 | 74.0 | 62.0 | 60.1 | 48.0 | 47.0 | 20.1 |

4 Test results and analysis

As shown in TABLE IV, the relevant dimensions of the test were measured prior to the test.

TABLE IV: OUTLINE MEASUREMENT DIMENSIONS

| NO. | 1 | 2 | 3 | Average |
|---|---|---|---|---|
| Outside diameter of copper /mm | 47.06 | 47.1 | 47.04 | 47.07 |
| Inner diameter of inner stainless steel /mm | 47.86 | 48.12 | 47.66 | 47.88 |
| Outside diameter of inner stainless steel /mm | 58.76 | 58.62 | 58.72 | 58.70 |

The difference of helium gap temperature between the measured value and the theoretical value are shown in *FIG. 4*. The helium temperature was measured under 7 cases(the linear power are 4.25 kW / m, 7.62 kW / m, 10.02 kW / m, 10.81 kW / m, 10.83 kW / m, 13.35 kW/m and 13.92 kW/m).

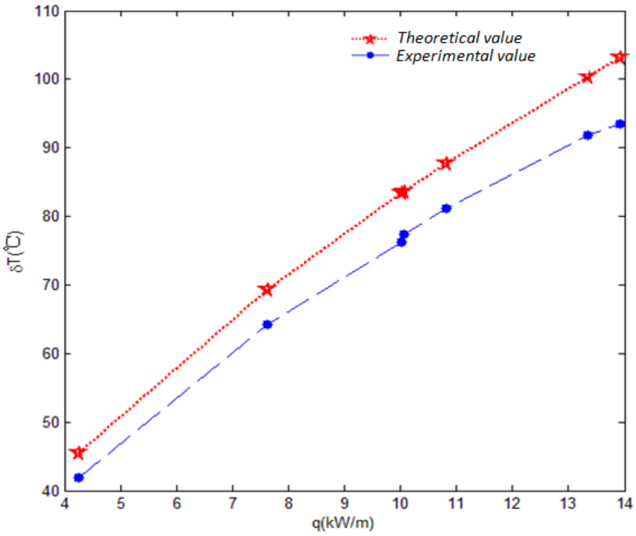

*FIG. 4. Comparison of experimental value and theoretical value*

In the figure, q is the linear power, δT is the helium gap temperature difference. It can be figured from *FIG. 4* that the difference between the theoretical and experimental results increases with the increase of the linear power. The theoretical calculation results are always larger than the experimental results, and the deviation reached a maximum of 10.26% when the test linear power is 13.92 kW/m.

## 5 Conclusion

In this work, helium gap conduction tests are carried out on the double helium gap conduction test facility. The theoretical calculation and experiment value are compared under the conditions of 7 kinds of linear power. The conclusions are as follows:

1) The maximum deviation between the theoretical calculation and experimental results for the helium gap thermal conduction is 10.26%, which shows that the research method is reliable.

2) The double-helium gap thermal conduction test proved that it is feasible to realize the irradiation temperature of sample using helium gap in the irradiated container of CEFR structural material.

Reference

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