Research on Low-Background Neutron Scattering Furnace and Perforated Heating Element at CSNS

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Abstract

Metal foil element furnaces are widely used in neutron scattering sample environments. However, since the metal foil blocks the neutron beam, these furnaces typically have a large background from the metal foil. Therefore, we designed a special heating element with an innovative perforated structure for the furnace. This novel heating element can significantly reduce the instrumental background, and is specifically applicable to the Multi-Physics Instrument and High-Pressure Neutron Diffractometer in CSNS. This structure reduces material obstruction of the neutron beam, thereby greatly lowering the experimental background. Additionally, we performed electro-thermal-mechanical coupled finite element simulation on the heating element to analyze its temperature and stress distribution, and identified the locations most susceptible to failure. We adjusted the heating element' s hole size to study temperature and stress changes, providing a theoretical basis for future optimization of the heating element. This furnace is extensively applied in CSNS, facilitating users in accomplishing neutron scattering experiments and achieving a series of research outcomes.

Full Text

Preamble

Research of Low-Background Neutron Scattering Furnace and Perforated Heating Element at CSNS

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Metal foil element furnaces are widely used in neutron scattering sample environments. However, since the metal foil blocks the neutron beam, these furnaces typically generate a large background signal from the metal foil itself. To address this issue, we designed a special heating element featuring an innovative perforated structure. This novel heating element can significantly reduce the instrumental background and is specifically applicable to the Multi-Physics Instrument and High-Pressure Neutron Diffractometer at CSNS. The perforated structure reduces material obstruction of the neutron beam, thereby greatly lowering the experimental background. Additionally, we performed electro-thermal-mechanical coupled finite element simulations on the heating element to analyze its temperature and stress distributions, identifying the locations most susceptible to failure. We adjusted the heating element' s hole size to study temperature and stress changes, providing a theoretical basis for future optimization. This furnace has been extensively applied at CSNS, enabling users to conduct neutron scattering experiments and achieve a series of research outcomes.

Keywords: Neutron scattering, Sample environment, Metal-foil element furnace, Perforated heating element

INTRODUCTION

Neutron scattering technology holds significant applications in physics[1], chemistry[2], biology[3],[4], materials science[5], and engineering[6],[7]. The China Spallation Neutron Source (CSNS)[8],[10] provides an essential experimental platform for neutron scattering experiments and related research. During neutron scattering experiments, sample environment devices are used to simulate material working conditions, such as high-temperature[11], high-pressure[12], or low-temperature environments[13],[14]. High-temperature sample environment devices are widely used in various fields, including measurements of stress-strain[15], crystal structure[16], and analysis of phase transitions[17]. For instance, Lu et al. conducted small-angle neutron scattering (SANS) experiments using a furnace at CSNS and investigated the continuous polymorphic transition in high-entropy metallic glasses lacking first-order transformation characteristics[18]. Song et al. employed furnace-based SANS experiments to examine the influence of aging time on austenite transformation, offering critical insights into the austenite-precipitate synergistic design strategy for controlling the mechanical properties of steels[19]. Additionally, M.V. Avdeev et al. utilized a furnace to explore the formation mechanisms of nanoprecipitates in Tb-doped $Fe_{81}Ga_{19}$ alloys[20].

Metal foil element furnaces are among the most commonly used furnaces in neutron scattering experiments. This type of furnace heats samples through radiation by loading high currents onto thin metal foils. However, because the metal foil heating elements must enclose the sample, this configuration tends to block the neutron beam and generate significant background signals. To reduce the background signal, extensive efforts have been undertaken by researchers. For example, researchers have replaced the materials of the metal foil heating elements from platinum[21] and tungsten[22] to niobium[23] and vanadium[24]. Additionally, researchers have reduced the number of thermal insulation screens[25] and employed radial collimators[26], among other methods.

In order to reduce experimental background from the heating element, a commonly employed method is to create holes in the heating elements, which can significantly decrease the background in neutron scattering experiments by reducing obstacles in the neutron beam path. The shape of the holes is generally rectangular[22] or circular[27] (primarily to match the size and shape of the neutron beam). While the holes can effectively reduce the background, they also lead to reduced heating efficiency, temperature inhomogeneity, and increased thermal stress. Since the temperature and thermal stress on the metal foil are difficult to measure, studies on the temperature and stress distribution of such perforated heating elements have been rarely reported to date.

In this article, a low-background metal foil element furnace—Hot-04—was designed, with a hole shape that differs from conventional rectangular and circular shapes. This furnace is used in neutron diffraction experiments on the Multi-Physics Instrument[28] and High-Pressure Neutron Diffractometer[29] at CSNS. It is capable of providing a maximum sample temperature of 1400 °C while maintaining a low background level. Additionally, we pioneer the application of electro-thermal-mechanical coupled finite element analysis to unveil the temperature distribution and thermal stress fields within perforated metal foil heating elements under operational conditions. The findings provide guidance for practical applications and performance optimization of such heating elements. Furthermore, the computational framework developed exhibits excellent reproducibility, enabling straightforward replication and extension of the numerical model by subsequent researchers. This methodology provides a robust foundation for advancing the design and analysis of perforated metal foil heating elements.

II. DESCRIPTION OF THE FURNACES

Figure 1: see original paper presents the system diagram of Hot-04. The vacuum pump can provide a vacuum level of 10^{-8} kPa, preventing high-temperature oxidation of the sample and the heating element. When required, an inert gas atmosphere can also be introduced into the system. The industrial computer, connected to a controller, regulates the current flowing through the heating element to generate the necessary heat. Meanwhile, a chiller is employed to control the temperature of the furnace outer wall via water cooling.

Figure 1: see original paper illustrates the structure of the Hot-04 furnace, where the sample is suspended at the center of the heating element. To prevent heat loss, thermal insulation screens are installed around the sample. Additionally, vacuum water-cooled chambers are positioned both above and below the sample. The neutron beam traverses these thermal insulation screens and the heating element prior to reaching the sample.

[Figure 2: see original paper] presents the structure of the heating element and the direction of current flow. The heating element is constructed from two niobium foils. Each foil is 0.05 mm thick and formed into a cylindrical shape with an open bottom. The foils are connected at the bottom by a 5-mm-thick niobium ring and welded to a niobium tube at the top. The niobium foils are 230 mm long, with an inner diameter of 50 mm for the inner layer.

To minimize background and enhance neutron beam transmission, two symmetrical perforations are opened in the middle of the heating element. These perforations, resembling keyways, are 18 mm wide and 56 mm long, with a rectangular center and semicircular ends (to match the size and shape of the neutron beam). They allow the neutron beam to pass through.

The current flows downward from electrode 1 through the outer niobium foil, then upward through the inner foil via the bottom annulus, and ultimately exits through electrode 2. Due to the proportional relationship between heat generation and current density, heat is concentrated in the thinner niobium foil at the bottom. The experimental sample, mounted on a sample rod, is fixed along the central axis of the heating element and adjusted to the keyway-shaped perforation height (the beam position) to achieve a high-temperature environment and complete the neutron scattering experiment.

III. SIMULATION METHOD

A. Boundary Conditions and Coupling Processes

Given that the majority of thermal energy in the heating assembly is localized within the niobium foil, and the sample mainly receives heat radiation from the niobium foil, we simulate only the niobium foil part to reduce computational cost.

As a typical thin shell with a thickness significantly smaller than its other dimensions, niobium foil is well-suited for shell element analysis[30]. COMSOL Multiphysics 6.1 was employed, integrating the following modules: "Layered Shell," "Heat Transfer in Shells," "Surface-to-Surface Radiation," and "Electric Currents in Layered Shells." These modules enable the simulation of three multi-physical fields: "Electromagnetic Heating, Layered Shell," "Heat Transfer with Surface-to-Surface Radiation," and "Layered Thermal Expansion." By adopting this approach, electric-heat-force coupling is achieved, resulting in the calculation of temperature and thermal stress distributions within the heating element.

Due to the difference in thickness between the niobium ring and the niobium foil on the heating element, a "Continuity" feature must be added for each physical field to ensure effective connection between shell elements of different thicknesses. The remaining boundary conditions are set according to the actual situation, as follows:

(1) In the context of "Electric Current in Layered Shells,"based on the direction of electric current flow, the top of the inner niobium foil is grounded, while the top of the outer niobium foil is set with a potential, creating a current flow that moves from the inner layer down, through the niobium ring, and then back up through the outer layer from bottom to top. According to the required operating temperature, the potential is increased or decreased to adjust the temperature conditions of the heating element and the sample. This is coupled with the "Heat Transfer in Shells" physical field to form an "Electromagnetic Heating, Layered Shell" multi-physics field, completing the simulation of current heating.

(2) In the "Surface-to-Surface Radiation" module, radiation is directed from the sample surface towards the heating element, with niobium foils radiating heat on both sides. The surface emissivity and the environmental radiation rate are both set to 0.35[31]. This is then coupled with the "Heat Transfer in Shells" physical field to form a "Heat Transfer with Surface-to-Surface Radiation" multi-physics field, enabling the simulation of heat transfer between the two layers of niobium foils and between the heating element and the sample.

(3) In the "Heat Transfer in Shells" module, maintain the default settings and couple it with other physical fields to form a multi-physics model.

(4) In the "Layered Shell" module, the "Rigid Motion Suppression" feature is applied to the heating element. This feature is designed to suppress the rigid body displacement and rotation of an object, making it particularly suitable for simulating thermal stress conditions under thermal expansion. When coupled with the "Heat Transfer in Shells" physical field, it forms a "Layered Thermal Expansion" physical field, which simulates the thermal stress conditions within the shell body due to temperature gradients.

B. Model Construction and Meshing

The two-step model is discretized using different meshing strategies. For the temperature simulation, a uniform mesh size is employed. In contrast, the stress simulation requires a more refined mesh, particularly at the joint between the niobium foil and ring, as well as near the opening, where stress concentrations are expected to occur. To ensure the accuracy of the calculation results, it is essential to verify grid independence and assess grid quality. The "degree of freedom" in COMSOL is utilized as an indicator to reflect computational complexity.

A grid independence verification study was conducted using five different mesh division cases. The analysis showed that both temperature and stress results exhibited negligible variations among these cases, with an average mesh quality exceeding 0.8. To optimize computational efficiency, the scheme with 82,022 degrees of freedom was selected for temperature simulation, while the scheme with 1,983,090 degrees of freedom was chosen for stress simulation.

The material of the niobium foil heating element is pure metallic niobium, with no other materials present. The material parameters of niobium are shown in .

Grid Independence Verification (temperature simulation) Degrees of freedom | Inner temperature gap 33,372 | 474 °C 82,022 | 477 °C 194,326 | 480 °C 287,778 | 477 °C 317,914 | 478 °C Mesh quality: >0.8

Grid Independence Verification (stress simulation) Degrees of freedom | Maximum stress | Mesh quality 1,600,890 | 19.5 MPa | >0.8 1,983,090 | 19.5 MPa | >0.8 2,703,570 | 19.5 MPa | >0.8 3,102,150 | 19.5 MPa | >0.8 3,360,030 | 19.5 MPa | >0.8

In this simulation, there are three multi-physics fields: "Electromagnetic Heating, Layered Shell," "Heat Transfer with Surface-to-Surface Radiation," and "Layered Thermal Expansion." The first two are related to temperature simulations, while the last one concerns stress simulations.

Since it is challenging to find a convergent solution for the temperature radiation simulation in steady-state conditions, a transient solver is employed with a time setting of 60 s, by which point the temperature has nearly reached equilibrium, and this is used as the basis for analysis of the simulation results. On the other hand, stress simulation can find a convergent solution in steady-state conditions, and steady-state is more computationally efficient, so a steady-state solver is used. Therefore, the simulation is conducted in two steps: the first step involves transient temperature simulation, and the results at 60 s from the transient simulation serve as the initial conditions for the second step, which is the steady-state stress simulation.

[Figure 3: see original paper] shows the grid division: (a) Meshing of temperature simulation; (b) Meshing of stress simulation.

C. Theoretical Equations

Joule heat is the only heat source Q, and its governing equation is:

$$Q = J \cdot E$$

Where J is the current density and E is the electric field strength.

In terms of heat transfer, since it is a vacuum environment and there is no heat convection, the main heat transfer modes are heat conduction and heat radiation. The governing equation of heat conduction in COMSOL is as follows:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q$$

Where is the material density, Cp is the specific heat capacity, T is the instantaneous temperature, t is the heat transfer time, u is the external field dependent variable in the convection term (which is zero in this model), and k is the thermal conductivity.

The governing equation for thermal radiation is:

$$e_b(T) = n^2 \sigma T^4$$

Among them, e_b(T) is the thermal radiation energy emitted by an object per unit time and per unit area as revealed by the Stefan-Boltzmann law. In this law, n represents the refractive index, which is equal to 1 in the case of heat propagation in a vacuum. The Stefan-Boltzmann constant, denoted by σ, is a fundamental constant of blackbody radiation, with a value of 5.67×10^{-8} $\mathrm{W/(m^2 \cdot K^4)}$. However, the radiating power of a real object often deviates from this idealized formula, and therefore, the emissivity is introduced as a correction factor. In COMSOL, a diffuse reflective surface is assumed to be a diffuse gray body by default, with equal absorptivity and emissivity that are independent of wavelength.

The governing equation of the "Multilayer thermal expansion" multi-physics field in COMSOL is as follows:

$$\varepsilon_{th} = \alpha (T - T_{ref})$$

Where _{th} is the thermal strain, α is the secant thermal expansion coefficient, and T_{ref} is the initial temperature of the object.

IV. SIMULATION RESULTS AND ANALYSIS

A. Temperature Distribution

To simulate actual experimental conditions, a radiation simulation was conducted. The sample' s working temperatures were set to 1200 °C, 1400 °C, and 1600 °C, and the temperature distribution of the heating element was simulated at each of these temperatures. For temperature calibration purposes, the temperature at the center of the sample was defined as the actual working temperature of the sample.

As shown in [Figure 4: see original paper], the presence of an opening in the middle of the heating element results in a temperature distribution where the lowest temperature is observed in the middle of the sample, opposite the opening, and the highest temperature is found at the bottom. The temperature difference between the bottom and the middle of the sample increases with the working temperature. Specifically, when the central temperature is 1200 °C, the temperature difference within the sample is approximately 3.6 °C. This difference increases to around 5 °C at a central temperature of 1400 °C, and to about 7 °C at 1600 °C. Notably, the temperature difference within the sample remains below 10 °C, indicating that the metal foil furnace exhibits excellent heating performance.

[Figure 4: see original paper] Sample temperature distribution: (a) Sample working temperature 1200 °C; (b) Sample working temperature 1400 °C; (c) Sample working temperature 1600 °C.

When the sample reaches the desired temperature, the temperature of the metal foil heating element itself is significantly higher than that of the sample. [Figure 5: see original paper] illustrates the temperature distribution of the heating element when the sample is at 1200 °C. The temperature trend of the heating element remains largely consistent across different sample temperatures. This is because, according to the governing equation of Joule heat, the sole heat source Q is directly proportional to the current density. Consequently, the temperature of the heating element is also proportional to the current density within it.

The simulation results reveal that the reduction in radius leads to an increase in current density, resulting in a significantly higher temperature in the inner layer of the niobium foil within the heating element compared to the outer layer. During radiation heating, the inner layer of the niobium foil serves as the primary heat source, and its high temperature is more conducive to efficient heating. Furthermore, the results show that in the unopened area, the radial temperature gradient is minimal, ensuring good temperature uniformity. In contrast, a substantial temperature difference is observed in the vicinity of the opening.

[Figure 6: see original paper] illustrates the axial temperature of the heating element when the sample reaches 1200 °C. [Figure 5: see original paper] Overall temperature of the heating element: (a) Outer layer of the heating element; (b)

Inner layer of the heating element.

[Figure 6: see original paper] shows the temperature distribution on the side of the heating element along the direction of current flow when the sample reaches 1200 °C. As previously mentioned, the current flows from top to bottom through the outer niobium foil, then through the bottom ring, and finally from bottom to top through the inner niobium foil. The figure reveals that the temperature of the upper part of the niobium foil is relatively low compared to the bottom and middle sections. This may be attributed to the fact that the upper part of the simulation model is open, resulting in partial heat loss, whereas the lower part is enclosed by a ring, which reduces heat loss. In contrast, the temperature on the side of the opening hole is relatively high, with the highest temperature appearing on the side of the inner layer of the opening hole.

[Figure 7: see original paper] depicts the temperature distribution at the opening of both the inner and outer layers when the sample reaches 1200 °C. The opening of the heating element features a keyway shape, formed by the combination of a rectangle and two semicircles. The highest temperature is observed at the junction of the rectangle and the semicircle. Notably, the side of the keyway-shaped perforation exhibits a significantly higher average temperature, exceeding that of other areas within the layer, while the temperature in the semi-circular regions is comparatively lower. This configuration results in a substantial temperature gradient, with the outer niobium foil experiencing a temperature difference of approximately 210 °C across the hole, and the inner niobium foil showing a difference of about 232 °C. Such significant temperature variations are expected to generate considerable thermal stress, which will be evident in subsequent stress analysis.

presents the temperature of the heating element at various sample temperatures. The "hole temperature difference" refers to the maximum temperature difference in the vicinity of the opening hole. For the other two cases, the temperature distribution trend is similar to that of the sample at 1200 °C, where the inner layer exhibits a higher temperature than the outer layer, and the temperature near the opening hole is higher than in other areas, resulting in a significant temperature difference near the opening hole. The opening affects the radiation efficiency, causing the inner temperature of the heating element to be substantially higher than the sample temperature. Furthermore, it is observed that the higher the temperature of the heating element, the greater the temperature difference near the opening hole, with the highest temperature difference reaching 336 °C at the inner layer opening hole.

The temperature of the heating element at different sample temperatures

Sample temperature	Maximum outer temperature	Minimum outer temperature	Maximum inner temperature	Minimum inner temperature	Outer hole temperature difference	Inner hole temperature difference
1200 °C	1202 °C	900 °C	1409 °C	1058 °C	210 °C	232 °C
1400 °C	1415 °C	1052 °C	1649 °C	1235 °C	257 °C	282 °C
1600 °C	1623 °C	1203 °C	1884 °C	1407 °C	308 °C	336 °C

B. Stress Distribution

Given the relatively small temperature difference in the sample, with a maximum of only 7 °C, and considering that the sample remains solid without any experimental damage, we can neglect its conditions and focus exclusively on the stress analysis of the heating element. The "Layered Shell" and "Layered Thermal Expansion" physical fields in COMSOL enable thermal stress analysis of shell elements. After applying "Rigid Motion Suppression" to constrain the object' s rigid body displacement, a stress singularity emerges at the junction of the bottom ring and the niobium foil. At this location, the stress results increase with mesh density, which is not representative of practical scenarios, as no failure phenomena are observed at the bottom joint in actual conditions.

According to the Saint-Venant principle[34], the specific load distribution has a minimal influence on the stress far from the load zone. Therefore, the stress singularity at the bottom joint does not significantly affect the stress results at a distance. Consequently, we disregard the stress results within 10 mm above the bottom connection and present the subsequent results.

[Figure 8: see original paper] shows the thermal stress of the heating element at different working temperatures. When the sample temperature reaches 1600 °C, the maximum stress at the opening hole reaches a peak value of 19.4 MPa, specifically at the four corners of the keyhole where the temperature difference is most pronounced. In other regions adjacent to the opening, the stress is distributed within a range of 5-19 MPa.

Except for the opening area, the stress surrounding the hole is relatively low, ranging from approximately 0.5 to 1 MPa. This reduced stress can be attributed to the uniform structure of the niobium foil in these regions, where temperature differences are minimal, potentially leading to stress relaxation and stress release. Notably, the inner layer opening of the heating element has reached a temperature of 1885 °C, which is close to niobium' s melting point of 2468 °C. As the temperature increases, the material' s yield strength decreases significantly. According to the literature[35], the yield strength of niobium at 1200 °C drops to 102.7 MPa from 287 MPa at room temperature. Extrapolating from this data, it is likely that the yield strength of niobium may have decreased to approximately 19 MPa or less when the inner layer hole temperatures reach around 1800 °C, potentially causing damage and deformation at and around the holes. Therefore, heating the sample to 1600 °C in daily use should be avoided, as this may damage the heating element.

[Figure 8: see original paper] Stress distribution of heating element: (a) 1200 °C; (b) 1400 °C; (c) 1600 °C.

C. Variable Aperture Simulation

After simulating the temperature and stress distributions of the current heating element, we found that the heating element' s perforations cause local temperature and stress variations, reducing its mechanical strength. For follow-up research on such perforated heating elements, we simulated different hole sizes.

The heating element features a keyway-shaped perforation with initial dimensions of 18 mm in width and 56 mm in length. We incrementally increased both the width and length of the keyway-shaped perforation and subsequently monitored the resulting temperature and stress changes under the specified boundary conditions, with the sample temperature maintained at 1600 °C.

illustrates the temperature conditions of different regions of the sample and the heating element when the width is increased. The "temperature difference" is defined as the difference between the maximum and minimum temperatures in a given layer. It can be observed that as the width of the opening increases, substantial heat leakage occurs in the middle region, leading to an increased temperature difference in the sample and a significant reduction in heating efficiency. To achieve the same sample temperature, a higher heating element temperature is required. Moreover, regardless of whether it is the inner or outer layer, an increase in width results in higher maximum temperatures and lower minimum temperatures, thereby further enlarging the temperature difference. When the opening width is increased to 28 mm, the temperature difference between the maximum and minimum temperatures reaches 574 °C, which is 100 °C higher than the temperature difference before the width was increased.

Figure 9: see original paper shows the temperature distribution on the inner side of the heating element when the keyway-shaped perforation width is changed. The distribution is characterized by higher temperatures in the middle and lower temperatures on both sides. The height of the opening is between 87 mm and 143 mm from the top. It can be observed that at the unopened height, the temperature decreases with increasing width; at the opened height, the temperature increases with increasing width. This phenomenon arises from the increased current density near the widened aperture relative to the baseline configuration, resulting in higher temperatures and a greater temperature difference, which in turn generates higher stress.

presents the temperature conditions of different regions of the sample and the heating element at various lengths. It can be observed that, with the width held constant, increasing the length results in a relatively small change in the temperature difference between the sample and the heating element. When the length of the opening is increased by 20 mm, the temperature difference in the inner layer is reduced by 13 °C. Figure 9: see original paper shows the temperature conditions on the inner side of the heating element when the length of the opening is changed. It is found that after the length is increased, the temperature at the opening height is significantly reduced, which leads to a noticeable decrease in the temperature difference in the non-opening regions and a more gradual temperature gradient. This suggests that moderately increasing the length of the opening can be considered as a potential optimization direction for the future.

Temperature at different opening widths Width | Maximum sample temperature | Minimum sample temperature | Sample temperature difference | Maximum inner temperature | Minimum inner temperature | Inner temperature difference | Maximum outer temperature | Minimum outer temperature | Outer temperature difference 18 mm | 1608 °C | 1599 °C | 10 °C | 1884 °C | 1407 °C | 477 °C | 1623 °C | 1203 °C | 420 °C 20 mm | 1589 °C | 1580 °C | 11 °C | 1892 °C | 1397 °C | 495 °C | 1628 °C | 1194 °C | 434 °C 22 mm | 1572 °C | 1563 °C | 11 °C | 1900 °C | 1388 °C | 512 °C | 1632 °C | 1186 °C | 446 °C 24 mm | 1556 °C | 1546 °C | 11 °C | 1910 °C | 1378 °C | 532 °C | 1636 °C | 1177 °C | 459 °C 26 mm | 1541 °C | 1530 °C | 12 °C | 1922 °C | 1366 °C | 556 °C | 1640 °C | 1169 °C | 471 °C 28 mm | 1526 °C | 1515 °C | 12 °C | 1935 °C | 1355 °C | 580 °C | 1643 °C | 1159 °C | 484 °C

Temperature at different opening lengths Length | Maximum sample temperature | Minimum sample temperature | Sample temperature difference | Maximum inner temperature | Minimum inner temperature | Inner temperature difference | Maximum outer temperature | Minimum outer temperature | Outer temperature difference 56 mm | 1608 °C | 1599 °C | 10 °C | 1884 °C | 1407 °C | 477 °C | 1623 °C | 1203 °C | 420 °C 60 mm | 1595 °C | 1587 °C | 9 °C | 1876 °C | 1402 °C | 474 °C | 1616 °C | 1198 °C | 418 °C 64 mm | 1583 °C | 1576 °C | 8 °C | 1869 °C | 1396 °C | 473 °C | 1610 °C | 1195 °C | 415 °C 68 mm | 1572 °C | 1565 °C | 8 °C | 1862 °C | 1393 °C | 469 °C | 1604 °C | 1192 °C | 412 °C 72 mm | 1562 °C | 1555 °C | 8 °C | 1854 °C | 1388 °C | 466 °C | 1598 °C | 1188 °C | 410 °C 76 mm | 1552 °C | 1546 °C | 7 °C | 1848 °C | 1384 °C | 464 °C | 1592 °C | 1184 °C | 408 °C

V. EXPERIMENTAL TEST

The preceding simulation analysis elucidates the temperature and stress distributions of the heating element and reveals the impact of the keyway-shaped perforation dimensions on the temperature and stress of the heating element. Currently, the Hot-04 furnace equipped with this type of heating element has been put into experimental operation on the Multi-Physics Instrument and High-Pressure Neutron Diffractometer at CSNS, providing experimental conditions for various scientific research endeavors.

Figure 10: see original paper presents the physical image of the heating element, while Figure 10: see original paper shows the actual configuration of the Hot-04 furnace. During the heating process, the furnace demonstrates the capability to elevate sample temperatures up to 1600 °C. Subsequent structural failure was observed to initiate specifically at the four corners of the keyway-shaped perforation, which further validates the accuracy of our simulation results. Under routine operating conditions, the furnace typically heats samples to a maximum temperature of 1400 °C, with no structural failure observed during standard usage.

Figure 10: see original paper displays the background data obtained through time-of-flight (TOF) neutron scattering measurements under unloaded conditions. A comparative analysis of neutron scattering spectra between niobium[36] and vanadium[37] reveals that the three Bragg peaks in Figure 10: see original paper originate from the vanadium windows of the furnace. No peaks associated with the niobium heating element were detected, demonstrating that this perforated heating element design significantly contributes to background reduction in experimental measurements. The experimental data from TOF neutron scattering measurements on a silicon sample using the Hot-04 furnace, as shown in Figure 10: see original paper, indicates that the furnace' s background has a negligible effect on the data. This suggests the furnace has excellent neutron transparency.

[Figure 10: see original paper] (a) Photograph of the heating element; (b) Photograph of the Hot-04 furnace; (c) Background data obtained through TOF neutron scattering measurements under unloaded conditions; (d) Experimental data from TOF neutron scattering measurements on Si sample.

VI. CONCLUSION

We propose the design of a low-background furnace, Hot-04, with a metal foil element. Its novel perforated heating element was subjected to finite element simulation. The temperature and stress distribution as well as vulnerable spots of this heating element were analyzed. Furthermore, the impact of varying hole dimensions on the temperature of the sample and heating element was examined. This study offers a theoretical basis for future development of such heating elements.

The following conclusions were drawn from the study:

(1) When the heating element is in operation, the inner niobium foil is 200-300 °C hotter than the outer one. The perforations reduce current pathways, increase current density, and create higher temperatures around the holes compared to other regions, with a maximum temperature difference of 336 °C at the edges of the holes.

(2) The large temperature difference due to the perforations causes a maximum stress of 19 MPa near the holes. The maximum stress appears at the four corners of the keyway-shaped perforation, which is the vulnerable spot.

(3) Increasing the hole width raises the temperature near the keyway-shaped perforations, lowers the temperature in non-perforated areas, increases the temperature difference, and reduces radiation efficiency to the sample. Increasing the hole length lowers the temperature near the keyway-shaped perforations, raises the temperature in non-perforated areas, decreases the temperature difference, and improves the stress situation. Moderately increasing the length is a potential optimization direction.

(4) The furnace with this perforated heating element has been used at CSNS, serving many users for neutron scattering experiments. It provides a high-temperature sample environment with low experimental background, barely affecting the neutron scattering experiments.

REFERENCES

[1] J.M. Song, W. Luo, B.Q. Liu, et al., Kunpeng: A cold neutron triple-axis spectrometer at CMRR in China. Nucl. Instrum. Methods Phys. Res. Sect. A. 968,163929(2020). doi: 10.1016/j.nima.2020.163929

[2] Y.X. Fan, Y.L. Wang, Applications of small-angle X-ray scattering/small-angle neutron scattering and cryogenic transmission electron microscopy to understand self-assembly of surfactants. Curr. Opin. Colloid Interface Sci. 42, 1-16(2019). doi: 10.1016/j.cocis.2019.02.011

[3] L.R. Zheng, L. Hong, Combining Neutron Scattering, Deuteration Technique, and Molecular Dynamics Simulations to Study Dynamics of Protein and Its Surface Water Molecules. Chin. J. Polym. Sci. 37(11), 1083-1091(2019). doi: 10.1007/s10118-

[4] T.T. Wang, D. Liu, X.B. Du, Recent progress in elastic and inelastic neutron scattering for chemical, polymeric, and biological investigations. Curr. Opin. Solid State Mat. Sci. 31,101175-101175(2024). doi: 10.1016/J.COSSMS.2024.101175

[5] C. Cheng, X.R. Xia, P. Wang, et al., Optimization of an inelastic neutron scattering facility and its application on bulk metallic materials measurement. Appl. Radiat. Isot. 194, 110687(2023). doi: 10.1016/J.APRADISO.2023.110687

[6] J.M. Xue, S. Feng, Y.H. Chen, et al., Measurement of the neutron-induced total cross sections of natPb from 0.3 eV to 20 MeV on the Back-n at CSNS. Nucl. Sci. Tech. 35, 18(2024). doi: 10.1007/s41365-024-01370-z

[7] J.K. Yang, P.Q. Wang, Z.M. Hu, et al., Research on perturbation of neutron fluence rate in a closed thermal neutron field due to medium materials. Nucl. Sci. Tech. 35(10), 185-185(2024). doi: 10.1007/s41365-024-01554-7

[8] H.S. Chen, X.L. Wang, China’ s first pulsed neutron source. Nat. Mater. 15(7), 689-691(2016). doi: 10.1038/nmat4655

[9] L. Tian, A. Salman, C.Y. Huang, et al., Developing time-of-flight polarized neutron capability at the China Spallation Neutron Source. Nucl. Sci. Tech. 34, 146(2023). doi: 10.1007/s41365-023-01286-0

[10] J.Y. Tang, Q. An, J.B. Bai, et al., Back-n white neutron source at CSNS and its applications. Nucl. Sci. Tech. 32(1), 11(2021). doi: 10.1007/S41365-021-00846-6

[11] H. Cheng, H.T. Hu, C.M. Hu, et al., An ultra-high temperature furnace for temperature determination by neutron resonance spectroscopy. Nucl. Instrum. Methods Phys. Res. Sect. A. 1049, 168072(2023). doi: 10.1016/J.NIMA.2023.168072

[12] Z.W. Ma, J. Lass, D. Mazzone, et al., Sourcing and reducing sample environment background in low-temperature high-pressure neutron scattering

experiments. Nucl. Instrum. Methods Phys. Res. Sect. A. 1066,169634(2024). doi: 10.1016/j.nima.2024.169634
[13] O. Kirichek, J.D. Timms, J.F. Kelleher, et al., Sample environment for neutron scattering measurements of internal stresses in engineering materials in the temperature range of 6 K to 300 K. The Review of scientific instruments, 88(2), 025103(2017). doi: 10.1063/1.4974815
[14] O. Kirichek, R.B.E. Down, J. Keeping, et al., Cryogen free sample environment for neutron scattering experiments at ISIS. J. Phys. Conf. Ser. 340, 012009(2012). doi: 10.1088/1742-6596/340/1/012009
[15] J.R. Santisteban, L. Edwards, M.E. Fitzpatrick, et al., Strain imaging by Bragg edge neutron transmission. Nucl. Instrum. Methods Phys. Res. Sect. A. 481(1-3), 765-768(2002). doi: 10.1016/S0168-9002(01)01256-6
[16] V.V. Sikolenko, V.V. Efimov, M.V. Silibin, et al., Investigation of the Crystal Structure and Magnetic Properties of $\mathrm{BiMnO_3}$ δ ($\delta = 0.08$ and 0.14) by the Methods of Neutron Diffraction and Magnetometry. J. Surf. Investig. 17, 1508-1513(2023). doi: 10.1134/S1027451023060447
[17] F.X. Shun, Q.J. Han, H.X. Zhen, et al., Unravel the Spinodal Decomposition Kinetics in $\mathrm{(FeCoCrNi)_{85}(AlCu)_{15}}$ Alloy through Small-Angle Neutron Scattering. Acta Metall. Sin.-Engl. Lett. 38(1), 86-92(2024). doi: 10.1007/s40195-024-01793-y
[18] Y.H. Cao, M. Yang, Q. Du, et al., Continuous polyamorphic transition in high-entropy metallic glass. Nature Communications. 15(1), 6702(2024). doi: 10.1038/s41467-024-51080-8
[19] C.H. Song, H.L. Wang, Z.Z. Sun, et al., Interaction of austenite reversion with precipitation/dissolution during aging in a medium Mn steel alloyed with Cu, Ni and Al. Materials Characterization. 181, 111486(2021). doi: 10.1016/j.matchar.2021.111486
[20] M.V. Avdeev, A.M. Balagurov, I.S. Golovin, Morphology and kinetics of nanoheterogeneities in $\mathrm{Fe_{81}Ga_{19}{-}Tb}$ alloy: A small-angle neutron scattering study. Physica B. 685, 416052(2024). doi: 10.1016/j.physb.2024.416052
[21] F.P. Bailey, C.E.G. Bennett, A simple furnace for neutron diffraction studies. J. Appl. Crystallogr. 12, 403-404(1979). doi: 10.1107/S0021889879012802
[22] J. Bletry, P. Taverniere, C. Senillou, et al., High-temperature furnaces for small and large-angle neutron-scattering of disordered materials. Revue de physique appliquee, 19(9), 725-730(1984). doi: 10.1051/rphysap:01984001909072500
[23] H.T. Hu, C.C. Zhang, M.J. Dou, et al., Experimental and numerical investigation the radiant heating element in neutron scattering furnace. Nucl. Instrum. Methods Phys. Res. Sect. A. 1053, 168317(2023). doi: 10.1016/j.nima.2023.168317
[24] D. Olds, R.A. Mills, M.T. McDonnell, et al., A high temperature gas flow environment for neutron total scattering studies of complex materials. Rev. Sci. Instrum. 89(9), 092906-092912(2018). doi: 10.1063/1.5033464
[25] J.L. Niedziela, R. Mills, M.J. Loguillo, et al., Design and operating characteristic of a vacuum furnace for time-of-flight inelastic neutron scattering measurements. Rev. Sci. Instrum. 88, 105116(2017). doi: 10.1063/1.5007089
[26] M.B. Stone, J.L. Niedziela, M.J. Loguillo, et al., A radial collimator for a

time-of-flight neutron spectrometer. Rev. Sci. Instrum. 85(8), 085101(2014). doi: 10.1063/1.4891302

[27] M. Kompatscher, M. Bär, J. Hecht, et al., A high-temperature cell for in situ small-angle neutron scattering studies of phase separation in alloys. Nucl. Instrum. Methods Phys. Res. Sect. A. 495(1), 40-47(2002). doi: 10.1016/S0168-9002(02)01565-6

[28] L. Zhu, J.R. Zhou, Y.G. Xia, et al., Large area ^{3}He tube array detector with modular design for multi-physics instrument at CSNS. Nucl. Sci. Tech. 34, 1(2023). doi: 10.1007/s41365-022-

[29] W.J. Luo, W.L. Cai, P. Wang, et al., Design of bandwidth choppers for the high-pressure neutron diffractometer at the CSNS. Nucl. Instrum. Methods Phys. Res. Sect. A. 1030, 166471(2022). doi: 10.1016/j.nima.2022.166471

[30] R. Tu, J.Q. Li, Y.H. Hwang, et al., Study of temperature uniformity and thermal storage performances of a shell-and-tube type phase change plate. Int. J. Refrig. 122, 69-80(2021). doi: 10.1016/j.ijrefrig.2020.11.001

[31] Q.W. Wang, P. Xiao, J.T. Yu, et al., Measuring normal spectral emissivities of niobium by a pulse-heating technique: 1000 K to the melting point. Chin. Opt. Lett. 4(12), 701-704(2006). doi: 10.1016/j.ijrefrig.2020.11.001

[32] M.W. Haynes, CRC Handbook of Chemistry and Physics, 96th Edition. Taylor and Francis:2015-06-09.

[33] L.Q. Chen, Study on preparation technology of low cost niobium oxide electrolytic capacitor. Tsinghua University. 2013.

[34] K. Yokota, F. Barthelat, Stiff bioinspired architectured beams bend Saint-Venant' s principle and generate large shape morphing. Int. J. Solids Struct. 274, 112270(2023). doi: 10.1016/j.ijsolstr.2023.112270

[35] C. Li, B.H. Zhu, S.T. Liu, Effects of Deformation and Heat Treatment Temperature on Microstructure and Properties of Pure niobium Pipe. Ningxia Engineering Technology. 10(02), 153-156(2011).

[36] M. Krzystyniak, M.J. Gutmann, G. Romanelli, et al., Nitrogen doping and the performance of superconducting radio-frequency niobium cavities: insights from neutron diffraction and neutron Compton scattering. Journal of Physics: Conference Series. 1055(1),012006(2018).

[37] W.C. Meng, R. Du, M. Tang, et al., Total neutron scattering and data analysis in a virtual experiment: a case study on heavy water with a vanadium calibration sample. Instrum. Sci. Technol. 49(5), 532-544(2021). doi: 10.1080/10739149.2021.1894170

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