Experimental Study on 100hour-Term Performance of High-Temperature Sodium Heat Pipes

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Abstract

High-temperature heat pipes, utilizing alkali metals as working fluids, are essential heat transfer components in cooling systems of nuclear reactors. To assess the long-term isothermal behavior and heat transfer performance variation of high-temperature sodium heat pipes, this research presents the design and construction of a long-duration experimental test rig for high-temperature heat pipes. A 100-hour experimental investigation was conducted under operating conditions of 900 °C. The results demonstrate that the heat pipes can operate stably for extended periods after startup. The average temperature at the condenser section gradually increased, while the overall temperature difference fluctuation decreased. The magnitude of temperature difference reduction was measured to be 2.3 °C, and the effective thermal resistance of the heat pipe decreased to 0.0639 K/W. These results suggest an enhancement in both the isothermal performance and heat transfer capability characteristics of the sodium heat pipe after long-term testing. This study provides valuable insights for the design and assessment of high-temperature heat pipe systems in nuclear reactor cooling applications.

Keywords: High-temperature heat pipe, sodium heat pipe, long-term test, isothermal performance, heat transfer performance.

1. Introduction

The high effective thermal conductivity of an alkali metal heat pipe enables heat to be transferred at high efficiency over considerable distances. Heat pipes are passive heat transfer devices that utilize the phase change of a working fluid to transfer heat from a hot source to a cooler sink [1]. The alkali metal heat pipe, in particular, offers exceptional thermal performance and reliability in high-temperature environments. In recent years, there has been an increasing interest in utilizing alkali metal heat pipes for cooling applications in advanced nuclear reactor systems. A number of reactor power system concepts have been developed or proposed with alkali metal heat pipes such as the Kilopower Reactor system [2]–[4], the MegaPower Reactor system[5]. In many of these applications, heat pipes are challenging to replace or even impossible to replace once installed. Therefore, the thermal performance and reliability of alkali metal heat pipes are of utmost importance for the sustained operation of reactors.

High temperature alkali metal heat pipes are composed of several key components, including the envelope, wick, end cap, and working fluids [6]. The envelope and wick provide the structural support for the heat pipe, while the working fluids play a critical role in the heat transfer process. The working fluids undergo continuous vaporization and condensation, exchanging heat between evaporation section and condensation section of the heat pipe. The performance and longevity of high-temperature alkali metal heat pipes are highly dependent on the compatibility between the structural materials, working fluids, and their purity. Any incompatibility between these components can lead to the formation of non-condensable gases, which can reduce the heat transfer efficiency and even result in heat pipe damage [7]. Therefore, ensuring material compatibility and high-purity working fluids is critical to the successful operation of high-temperature alkali metal heat pipes.

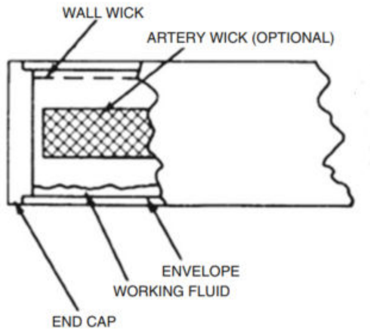

Fig. 1 Typical alkali metal heat pipe components [6]

A significant number of researches have been conducted to investigate the long-term operation characteristics of high temperature alkali metal heat pipes. These researches have focused on various aspects, including material selection, design parameters, working environment, operating temperature, and working fluid. Researchers at the Los Alamos National Laboratory have conducted experiments on the compatibility between alkali metals and high-temperature alloys, as well as the feasibility of long-term operation of high-temperature heat pipes [7], [8]. The experimental results have shown promising performance of alkali metal heat pipes in high-temperature environments. Thermacore, Inc.,[9] has carried out a 10-year durability test of a high-temperature heat pipe using sodium as the working fluid, Inconel 718 as the outer shell, and 316L as the wick material. The test ran for over 87,000 hours at nearly 700°C and was applied in a space Sterling engine. The results showed that the heat pipe performed well throughout the 10-year test, with no significant failures observed. The SEM characterization after the test revealed that although there was some element migration between the structural materials, there was no apparent degradation of the outer shell and wick core materials.

Table 1 Long-term operation of alkali metal heat pipes [10]

Fluid	Material	T(K)	Time(hrs)
Li	W-26Re	1875	10,000
Li	TZM	1775	10,500
Li	Nb-1Zr	1775	9,000
Li	Mo-13%Re	1500	11,400
Li	Molybdenum	1700	25,400
Na	Mo-TZM	1390	53,000
Na	Molybdenum	1400	45,000
Na	300-series SS	970	115,000
Na	Inconel-718	970	41,000
Na	Haynes-230	970	20,000
K	Nb-1%Zr	1350	10,000
K	300-series SS	920	5,300
K	Titanium	800	5,000
Hg	300-series SS	600	10,000

Meanwhile, the thermal characteristics of heat pipes can undergo changes over their operational lifetimes, potentially influencing their overall performance. In a study conducted by Yamamoto et al. [11], the long-term operation of sodium heat pipes was investigated to analyze the corrosion behavior and thermal resistance variations. The test results revealed that the corrosion of the heat pipe wall did not significantly affect the heat transfer efficiency of the heat pipe. It was observed that during the initial stages of the experiment, the total thermal resistance of the heat pipes gradually decreased. As the experiment progressed, the thermal resistance of the heat pipes approached a stable state, indicating a steady-state thermal performance.

However, most existing research on the long-term performance of sodium heat pipes has focused on those filled with liquid sodium [12]–[15], while studies on solid-state filled sodium heat pipes utilizing vacuum laser welding technology are limited. In this study, we address this research gap by investigating a high-temperature sodium heat pipe that employs a novel manufacturing process. We have developed a dedicated testing platform to conduct a 100-hour heat transfer experiment on this heat pipe under vertical operating conditions. The objective of this study is to analyze the wall temperature data and investigate the changes in heat transfer performance throughout the testing period.

2. Experiment Description

2.1 Preparation Methods of Alkali Metal Heat Pipes

Alkali metal heat pipes require a high vacuum environment within the vapor chamber during the manufacturing process. Conventional fabrication methods typically involve liquid sodium filling, where distilled sodium is introduced into the heat pipe after the degassing process, followed by sealing the fill tube using cold pressing and argon arc welding [6], [16]–[18]. In this paper, we propose a novel approach that employs a room-temperature solid-state sodium filling technique and utilizes laser welding within a high-vacuum glovebox for sealing the heat pipes.

The use of solid-state sodium filling technique in the manufacturing of high-temperature heat pipes offers several advantages over traditional methods. By introducing the sodium in its solid state, the safety and stability of the manufacturing process are significantly enhanced. Moreover, the solid-state filling process ensures precise control over the amount of sodium introduced into the heat pipe, leading to improved performance and stability. Additionally, this novel manufacturing approach allows for the optimization of heat pipe design by utilizing specially designed end caps instead of fill tubes. This design optimization not only improves the overall performance of the heat pipe but also provides space-saving benefits for various heat pipe applications. The main parameters of the heat pipe are listed in Table 2.

Table 2 Parameters of the sodium heat pipe

Parameter	Unit	Value
Outer diameter	mm	20.0
Length of heat pipe	mm	820.0
Wall thickness	mm	2.0
Envelope material		SS316L
Thickness of wick	mm	0.5
Mesh number of wick		200.0
Material of wick		SS316L
Length of evaporation section	mm	400.0
Length of adiabatic section	mm	35.0
Length of condensation section	mm	385.0
Quantity of sodium contained	g	15.06
Encapsulation vacuum	Pa	$2.7 * 10^{-4}$

The alkaline metal heat pipe casing material investigated in this experiment demonstrates excellent oxidation and corrosion resistance at high temperatures, allowing it to maintain good strength under high-temperature conditions [19]. The generated oxide layer is relatively thin and does not significantly affect the heat transfer of the heat pipe. Therefore, it is unnecessary to design an inert gas atmosphere for the experimental setup. The sodium heat pipe used in this experiment undergoes a preheating process before formal testing. Preheating of the sodium heat pipe was conducted to ensure optimal performance. The results of the preheating phase indicated the formation of a uniform oxide layer on the surface of the sodium heat pipe.

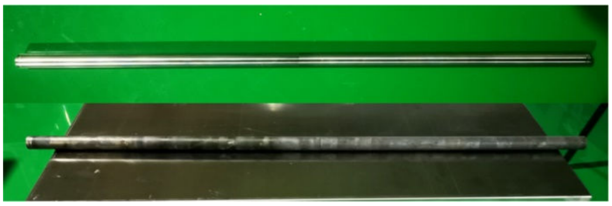

Fig. 2 Comparison before and after heat pipe preheating

2.2 Experimental System

The schematic diagram of the long-term test rig for alkaline metal heat pipes is shown in Fig. 3, while Fig. 4 presents an actual photograph of the assembled rig. The setup primarily consists of a high-temperature sodium heat pipe, a heating system, an air-cooling system, and a temperature data acquisition system. Safety measures have been implemented in the power supply section and the temperature alarm settings of the instruments to prevent overheating accidents and ensure the overall safety of the experimental rig. The constructed experimental rig enables measurement of the temperatures at various points on the high-temperature sodium heat pipe, as well as the temperature and flow rate of the inlet and outlet air. This facilitates the analysis of the heat pipe's long-term isothermal characteristics and heat transfer performance after extended operation.

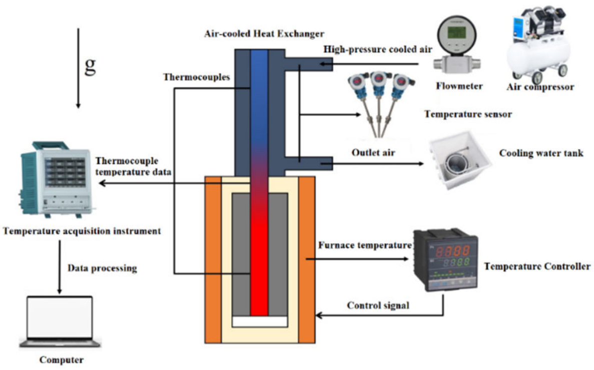

Fig. 3 Sodium heat pipe long time test bench diagram

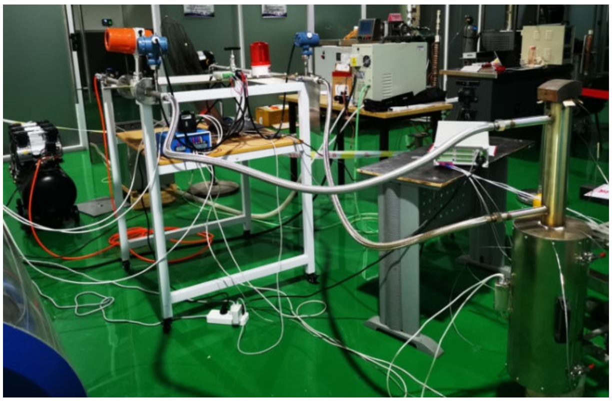

Fig. 4 Sodium heat pipe long time test bench physical picture

The system consists of a vertical constant temperature furnace with a rated power of 4.2 kW, equipped with a temperature control system to maintain a constant furnace temperature. Temperature data is collected using a K-type armored high-temperature thermocouple and a multi-channel temperature acquisition instrument. The thermocouples are strategically placed at the evaporator, insulation, and condenser sections of the heat pipe, with 3, 1, and 4 thermocouples deployed, respectively. The arrangement of the thermocouples is illustrated in the Fig. 5. In order to ensure a stable cooling medium for the condenser section of a heat pipe and achieve accurate measurement of the condensation power, this experimental setup incorporates an air-cooled sleeve, an air compressor, a coil heat exchanger, and data sensors to form a comprehensive cooling system.

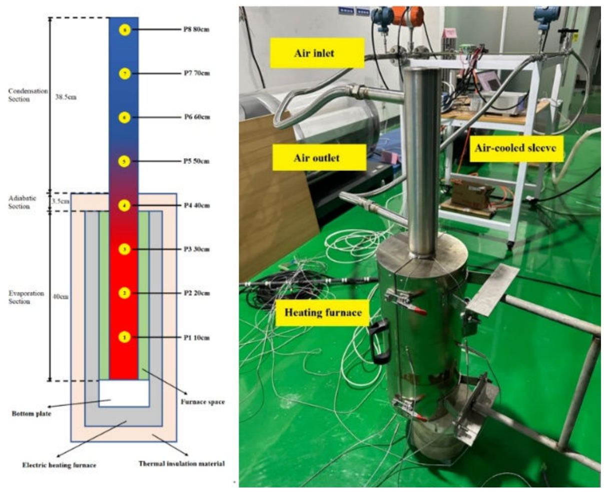

Fig. 5 Heat pipe thermocouple layout diagram (left) and actual experimental layout diagram (right)

2.3 Uncertainty analysis

In the experimental process, the errors associated with the data are inevitable. The main sources of uncertainty in this experiment arise from the maximum allowable error limits of the instruments used and the quantization error of the data acquisition card. Uncertainties introduced by factors such as connecting wires and operating temperature are disregarded. The measurement error in the wall surface temperature for this experiment is attributed to the maximum allowable error limit of the thermocouple and the indication error of the temperature measurement instrument. K-type armored thermocouples are employed to measure the temperature at the measurement point, with a maximum allowable error limit of 0.5°C. The uncertainty introduced by the temperature measurement instrument is significantly smaller compared to the uncertainty introduced by the thermocouple itself. Therefore, the total standard uncertainty for the wall surface temperature measurement is determined using Equation (2-1).

$$U_T = \Delta = 0.5°\mathrm{C} \tag{2-1}$$

The temperature measurement of the inlet and outlet air is carried out using an integrated temperature transmitter, which has an accuracy of 0.5% of the full scale range (0 to 400 °C). The DAM-3158 data acquisition module has an accuracy of 0.1%. It should be noted that the data acquisition module collects analog signals in the range of 4 to 20 mA, and in order to convert this signal into temperature values, a conversion factor of 25 is applied. Therefore, the total uncertainty for the measurement of the inlet and outlet air temperatures is determined using Equation (2-2). The total uncertainty of the air flow measurement is given by equation (2-3).

$$\begin{aligned} U_{T_{air}} &= \sqrt{{U_1}^2 + {U_2}^2} \\ &= \sqrt{(400 \times 0.2\%)^2 + (20 \times 25 \times 0.1\%)^2} \\ &= 0.943°\mathrm{C} \end{aligned} \tag{2-2}$$

$$\begin{aligned} U_{flow} &= \sqrt{{U_1}^2 + {U_2}^2} \\ &= \sqrt{(80 \times 1.5\%)^2 + (20 \times 5 \times 0.1\%)^2} \\ &= 1.204\mathrm{m}^3 \cdot \mathrm{h}^{-1} \end{aligned} \tag{2-3}$$

The temperature of each section of the heat pipe is obtained by averaging the thermocouple readings of each section, and the temperature of each section is obtained by (2-4) – (2-6).

Evaporation section average temperature:

$$T_e = \frac{T_1 + T_2 + T_3}{3} \tag{2-4}$$

Adiabatic section temperature:

$$T_a = T_4 \tag{2-5}$$

Condensation section average temperature:

$$T_c = \frac{T_5 + T_6 + T_7 + T_8}{4} \tag{2-6}$$

The isothermal property of heat pipe is usually evaluated by the temperature difference between the evaporation section and the condensing section of the heat pipe. Under the same heat transfer, the smaller the temperature difference of the heat pipe, the stronger the heat transfer capacity of the heat pipe. The temperature difference of the heat pipe is calculated by equation (2-7).

$$\Delta T = T_e - T_c \tag{2-7}$$

The heat transfer in the condensing section of the heat pipe is calculated by the heat absorbed by the compressed air, and the heat transfer power of the heat pipe is obtained by the cooling power of the gas-cooled sleeve. When the heat pipe is successfully started and reaches steady state, the cooling power of the heat pipe is calculated by equation (2-8).

$$Q = \rho_p V c_p (T_{out} - T_{in}) \tag{2-8}$$

In the above formula, V stands for volume flow of air, $m^3 \cdot h^{-1}$; T_{in} and T_{out} represent the temperature of the inlet and outlet air respectively, °C; ρ_p represents the density of air at different pressures, $kg \cdot m^{-3}$; c_p represents the specific heat capacity of air at constant pressure, $c_p = 1.01kJ \cdot kg^{-1} \cdot K^{-1}$.

The heat transfer capacity of heat pipes is evaluated by equivalent thermal resistance, which is calculated by equation (2-9).

$$R_{eq} = \frac{\Delta T}{Q} \tag{2-9}$$

3. Results and discussions

3.1 Analysis of heat pipe temperature variations

The experimental setup successfully conducted a 100-hour long-term test on high-temperature sodium heat pipes. The axial temperature distribution of the heat pipes throughout the entire test phase is shown in Fig. 6. From the graph, it can be observed that the temperatures at various measurement points remained remarkably stable during the 100-hour period, with no significant temperature drop. The temperature difference between the evaporator and condenser sections also exhibited consistent behavior. These experimental results demonstrate that the high-temperature heat pipes, utilizing solid sodium as the working fluid and employing vacuum laser welding technology, can operate continuously and reliably for a minimum of 100 hours under a constant furnace temperature of 900 °C.

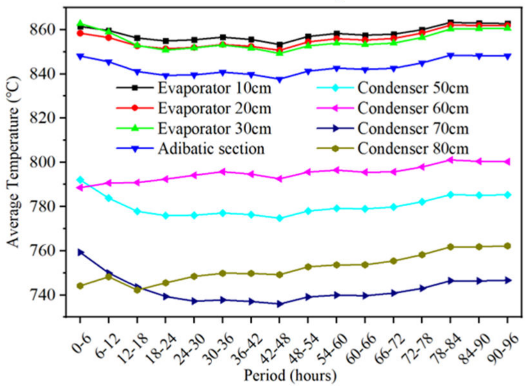

Fig. 6 Temperature distribution of heat pipe during 100 hours experiment

The average temperatures of the six measurement points on the evaporator section, adiabatic section, and condenser section at 70 cm and 50 cm exhibit a trend of initially decreasing and then increasing during each time interval. Additionally, the average temperatures of the eight measurement points tend to stabilize in the last three time intervals, indicating that the heat pipe has entered a relatively stable operating state. The temperatures of the last two measurement points in the condenser section are lower compared to the first two points. This is because the area above the gas-cooled sleeve serves as the inlet, where the cooling effect is more pronounced, resulting in lower temperatures.

The temperatures of the adiabatic section of the heat pipe and the topmost point of the condenser section are of significant importance in evaluating the operational state of the heat pipe. Due to the minimal heat losses in the adiabatic section of the heat pipe, the wall temperature of the evaporator section can reflect the temperature of the vapor inside the heat pipe. Fig. 7 illustrates the average temperatures of the adiabatic section measurement points during different time intervals. It can be observed that, as the heat pipe operates, the temperature of the adiabatic section initially decreases and then increases, indicating a similar trend in the temperature of the internal vapor.

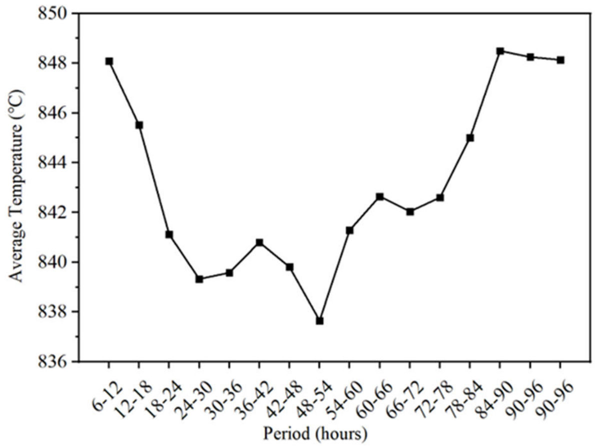

Fig. 7 Temperature change diagram of measuring point temperature at different time in adiabatic section

If the temperature at the topmost point of the heat pipe is higher, it indicates that the heat from the evaporator section is effectively transferred through the phase change of the working fluid to the entire condenser section, allowing the entire condenser section to participate in the heat transfer process and improve the heat transfer power of the heat pipe. From Fig. 8, it can be observed that as the operating time increases, the temperature of the last measurement point in the condenser section shows an upward trend. It increases from 742 °C in the 18-hour interval to 762 °C in the 96-hour interval, with an increase of 20 °C. This indicates that the heat transfer performance of the heat pipe in the condenser section is improving. It also confirms that there is no accumulation of non-condensable gas in the upper part of the condenser section, validating that the working fluid filling process in the manufacturing process of the alkali metal heat pipe, using the innovative vacuum welding technique, did not introduce non-condensable gases.

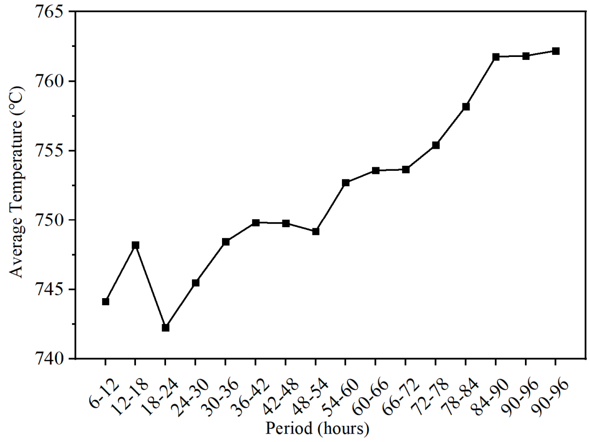

Fig. 8 The temperature of the measuring point at the end of the condenser section changes with time

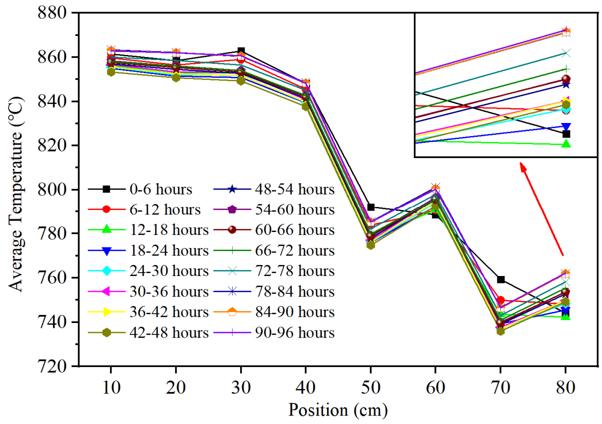

Fig. 9 Axial temperature distribution of heat pipe at different times

Fig. 9 illustrates the temperature distribution at different measurement points of the heat pipe during different time intervals. It can be observed that, except for the initial 24-hour period, the temperature variation trends at different measurement points of the heat pipe are essentially the same, with parallel curves and no significant temperature changes, confirming the excellent thermal uniformity performance of the high-temperature heat pipe.

Moreover, Fig. 10 demonstrates that with an increase in experimental time, the overall temperature difference of the heat pipe demonstrates a decreasing fluctuation trend, with a reduction of 2.3 °C. This indicates an improvement in the isothermal and heat transfer performance of the heat pipe, thereby confirming the advanced and feasible nature of utilizing solid-state filling technology and vacuum laser welding in the manufacturing of high-temperature heat pipes.

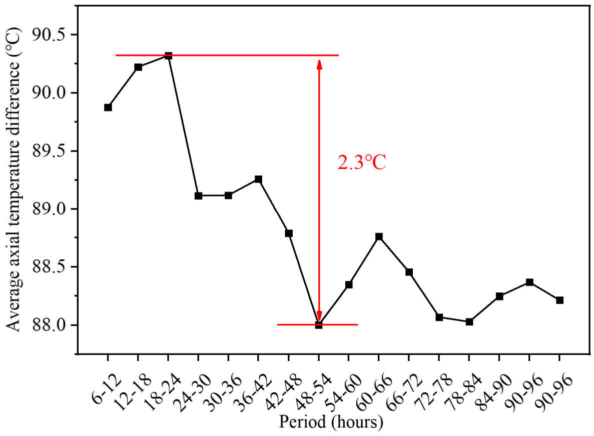

Fig. 10 The overall temperature difference of the heat pipe changes with time

3.2 Analysis of heat transfer performance

Since the discharge pressure of the air compressor fluctuates periodically within a certain range, the cooling power also exhibits cyclic variations. Fig. 11 illustrates the changes in cooling power, the temperature at the last measurement point in the condenser section, and the temperature at the first measurement point in the evaporator section over a specific time interval. It is evident that the cooling power undergoes periodic fluctuations over time, and the temperature in the condenser section of the heat pipe decreases almost simultaneously with the increase in cooling power. Due to the unique characteristics of heat transfer in the evaporation and condensation processes of the heat pipe, the temperature variations in the condenser section are subsequently responded to by the evaporator section, with a response time of approximately 180 seconds, leading to changes in the temperature of the evaporator section.

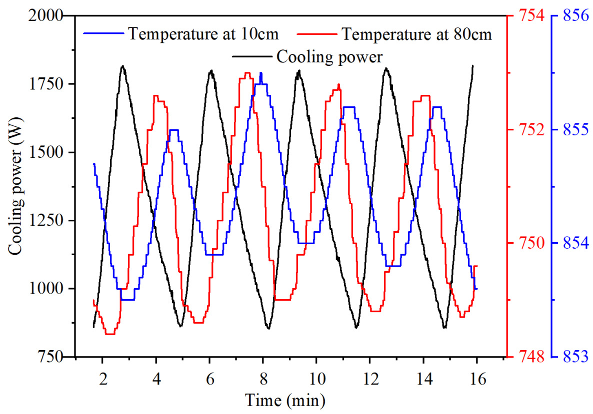

Fig. 11 Variation of heat pipe evaporation section temperature and condensation section temperature with cooling power

The relationship between the heat transfer power and the equivalent thermal resistance of the heat pipe over the entire 100-hour experimental period is shown in Fig. 12. It can be observed that the cooling power of the heat pipe reached its maximum value of 1380 W during the last time interval of the experiment, while the thermal resistance of the heat pipe reached its minimum value of 0.0639 K·W−1. This aspect confirms that the heat transfer performance of the heat pipe gradually improved as the experiment progressed. Using the equivalent thermal resistance of the heat pipe as a heat transfer indicator, the heat transfer performance of the heat pipe at the end of the experiment improved by 6.7 compared to the beginning of the experiment.

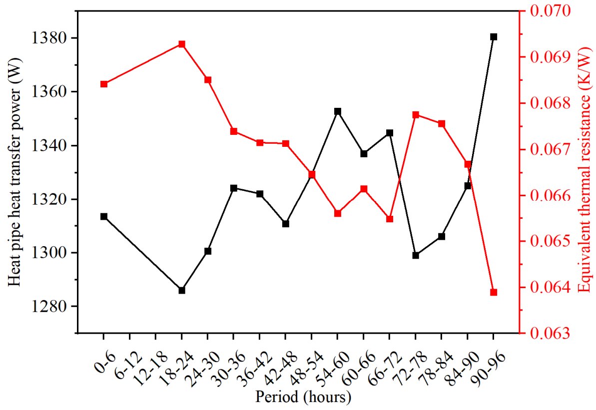

Fig. 12 The heat transfer power and equivalent thermal resistance of the heat pipe change with time

4. Conclusions

The high-temperature alkali metal heat pipe, without a filling tube and utilizing our team's novel solid sodium filling and vacuum laser welding process, has been successfully developed. A long-duration experimental setup for high-temperature heat pipes was designed and constructed, and a 100-hour experimental study was conducted under vertical working conditions. The experimental conclusions can be summarized as follows:

(1) The sodium heat pipe using this process demonstrated excellent reliability and operational stability, successfully operating for 100 hours under vertical working conditions at a heating temperature of 900 °C.

(2) The heat pipe's isothermal behavior and heat transfer performance gradually improved over time. The equivalent thermal resistance of the heat pipe reached a minimum value of 0.0639 K/W at the end of the experiment.

(3) The temperature of the heat pipe's evaporator section varied with changes in the condenser section's heat transfer conditions, exhibiting a certain time lag of approximately 180 seconds.

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