

Experimental Study on the Thermal Performance of a Sodium Heat Pipe Assembly for Space Nuclear Reactors

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1. Introduction

Korea Atomic Energy Research Institute (KAERI) has been developing key technologies for a space nuclear reactor, including core concepts and analysis codes [1]. A bendable sodium heat pipe was previously developed to transfer heat from the reactor core to Stirling engines, accompanied by experimental thermal performance evaluations [2]. This study aims to generate test results for a heat pipe assembly comprising six sodium heat pipes, using a graphite block to model the reactor core. These results will facilitate precise measurements of each heat pipe's heat transport capacity and serve as a basis for code validation [3]. The primary objective is to achieve a heat transfer rate exceeding 2.5 kW through the assembly at operating conditions with a working temperature of 650°C or higher.

2. Experimental Facility

An experimental apparatus was constructed to assess the thermal performance of an assembly composed of six straight sodium heat pipes. Fig. 1 shows the schematics of this experimental facility designed to evaluate the thermal performance of the assembly. Each 1 m-long, 1/2 inch diameter sodium heat pipe utilizes a hybrid braided-sintered wick design. The lengths of the evaporator, adiabatic, and condenser sections are 250 mm, 500 mm, and 250 mm, respectively.

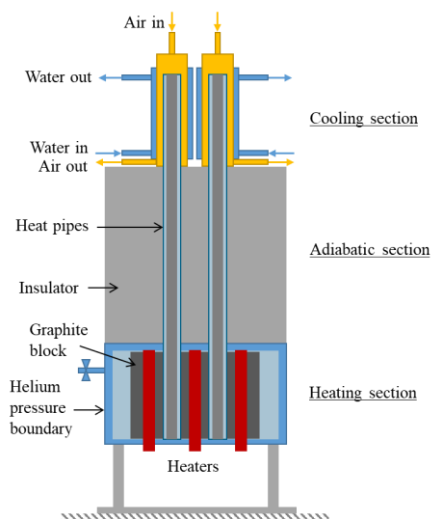


Fig. 1. Schematics of the experimental facility for the sodium heat pipe assembly.

2.1 Heating Section

The core of a space heat pipe-cooled reactor is typically designed with a hexagonal structure. Accordingly, the core structure of the heating section features a hexagonal design housing six heat pipes and 18 cartridge heaters, as depicted in Fig. 2. This core structure is manufactured using IG-11 graphite and has a height of 25 cm. The diameters of the heat pipes, heaters, and thermocouples are 1/2 inch, 12 mm, and 1/8 inch, respectively. To prevent oxidation of the graphite block during the experiment, the heating section was placed inside a helium chamber for insulation and sealing. The internal diameter of the helium chamber is 620 mm, and the graphite block is surrounded by ceramic board insulators.

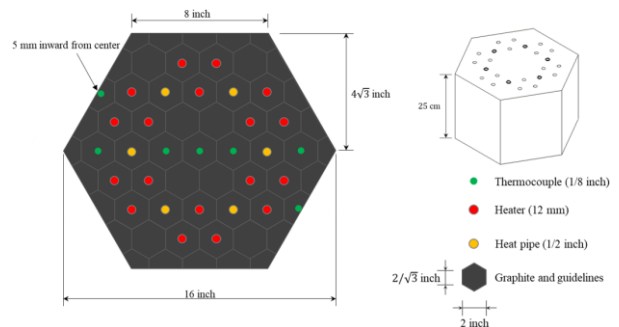


Fig. 2. Schematics of the core structure for the heating section.

2.2 Main Frame and Adiabatic Section

The main frame was constructed to provide space for inserting heaters and thermocouples at the bottom of the helium chamber and to fix the insulation box for insulating the adiabatic section of the heat pipe assembly. Each heat pipe is wrapped with cylindrical ceramic board insulators, and the outer area is further insulated with the insulation box to prevent heat loss through the adiabatic section.

2.3 Cooling Section

The cooling section of the sodium heat pipe assembly features a dual cooling structure that utilizes both air and water. Fig. 3 illustrates a cross-sectional view of the cooling section for the assembly, providing the dimensions of the air and water cooling paths. The water cooling jacket indirectly removes heat from the heat

pipes through radiative heat transfer, thereby preventing excessive cooling beyond the heat transport capability of the heat pipes. Complementing the water cooling system, the air cooling jacket provides forced convection cooling to enable precise and controlled heat removal.

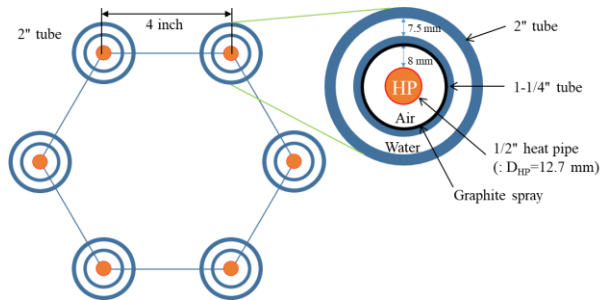


Fig. 3. Cross-sectional view of the cooling section.

2.4 Instrumentation and Control

In this study, a data acquisition (DAQ) system using NI cDAQ was established to collect measured data and manage signal outputs. LabVIEW software was employed to gather data and control the equipment of the experimental apparatus through signal outputs.

The temperature distribution inside the graphite block is measured using multi-point thermocouples at positions 5 cm, 12.5 cm, and 20 cm from the end of the evaporator section of the heat pipes. Wire-type thermocouples are affixed to the heat pipe surfaces to measure temperatures at the adiabatic section. The inlet and outlet temperatures of the water and air used for cooling are continuously measured to quantify the heat transfer performance through the heat pipe assembly.

The heaters in the heating section are controlled via a power supply regulated by DAQ analog output signals through Thyristor Power Regulators (TPR). The airflow from the blower and the water flow controlled by the liquid mass flow controllers are also regulated using DAQ analog output signals.

3. Preliminary Test Results

As a preliminary experiment, a startup test of the heat pipe assembly consisting of six sodium heat pipes was conducted without installing the condenser cooling jackets. The objective of this experiment was to identify optimal startup conditions that would not cause performance limitations during cold startup or thermal transport in the heat pipe assembly. This was achieved by evaluating whether the heat pipes could initiate proper operation under specific heat input conditions.

Fig. 4 shows the temperature measurement results at the adiabatic section (40 cm and 60 cm positions) for each sodium heat pipe. Five out of the six heat pipes, except for Heat Pipe #4, exhibited startup behavior in their adiabatic sections. Only Heat Pipe #6 showed complete startup up to the end of the condenser section. Although Heat Pipes #1, #2, #3, and #5 operated at higher temperatures than Heat Pipe #6, none of them

achieved complete startup along the full length of the condenser section.

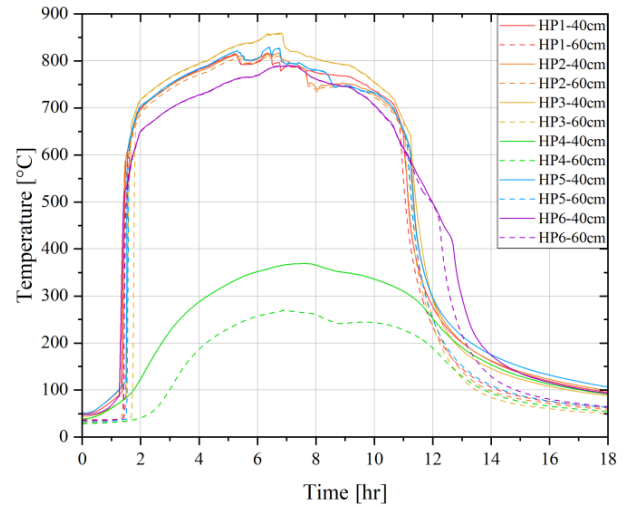


Fig. 4. Temperature profiles at the adiabatic section (40cm and 60cm) over time.

After 7.3 hours of operation, radiative heat transfer from the surfaces of the 1/2-inch heat pipes was quantitatively estimated, as summarized in Table I; the surface temperature at the 80 cm position was used to approximate the condenser section temperature for this calculation. An emissivity of 0.9 was assumed, reflecting the oxidized surface condition of the heat pipes. Based on the Stefan–Boltzmann law ($P = A\epsilon\sigma T^4$, where P is the radiated power, A is the surface area, ϵ is the emissivity, and $\sigma = 5.67 \times 10^{-8} W/m^2 \cdot K^4$ is the Stefan-Boltzmann constant), it was estimated that Heat Pipes #1, #2, #3, and #5—each with only about 15 cm of active heat transfer length—transferred approximately 330 W to 390 W of heat, while Heat Pipe #6 transferred about 590 W. In total, the five active heat pipes were estimated to have transported approximately 2 kW of heat.

Table I. Estimated radiative heat transfer for each heat pipe

	HP1	HP2	HP3	HP4	HP5	HP6
Surface temperature [°C]	756	745	787	-	768	765
Operational length in the condenser section [cm]	15	15	15	-	15	25
Emissivity	0.9	0.9	0.9	-	0.9	0.9
Heat transfer amount [W]	342	328	386	-	359	591

The observed discrepancy in the startup behavior and heat transport among the heat pipes may be attributed to several potential factors. Oxidation of the graphite under high-temperature conditions could lead to gap formation, thereby altering the thermal contact resistance. Alternatively, slight variations in the arrangement of the wick structure during the manufacturing process could

be a contributing factor. Further individual heat pipe tests and improvements to the assembly testing setup are planned to identify the exact cause of these issues before conducting the main experiments.

4. Conclusions and Future Works

In this study, an experimental apparatus was constructed to evaluate the thermal performance of a heat pipe assembly consisting of six 1-m-long bendable sodium heat pipes. A hexagonal graphite block was placed in the heating section to simulate the core of a heat pipe-cooled reactor. Six heat pipes and 18 cartridge heaters were embedded into the graphite block within a helium chamber. The cooling section was designed with a dual cooling structure that employs both water and air to minimize heat loss and precisely control the thermal performance of the heat pipe assembly.

As a preliminary experiment, a startup test of the heat pipe assembly was conducted without the cooling jackets. It was found that while five of the six heat pipes initiated startup in the adiabatic section, only one heat pipe successfully achieved full activation along the entire condenser length, despite the others operating at higher temperatures. The heat transport capability of the heat pipe assembly was quantitatively estimated to be approximately 2 kW through radiative heat transfer.

Future experiments will be conducted with the cooling jackets for heat transfer quantification, including various transient scenarios—such as the individual heat transport performance of each heat pipe—to further expand the validation dataset. The startup behavior and graphite block temperature distributions obtained from these experiments will be used to validate thermal design and analysis codes for space-based heat pipe-cooled reactors, including the core-level heat transport code.

ACKNOWLEDGMENTS

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