

Fundamental Experimental Study and Preliminary Heat Loss Estimation of a Vertical Sodium Heat Pipe with Hybrid Wick

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1. Introduction

Recently, many micro reactors for space applications have regained significant attention as an alternative to overcome the limitations of solar power systems in long-term missions such as deep space exploration, construction of lunar outpost or Martian bases. The space environment has extremely harsh conditions including cryogenic temperature, high vacuum environment, high level of radiation, and long-term operational requirements without human intervention. Nuclear energy has been evaluated as the most effective technology to overcome these requirements by using continuous power supply with high energy density.

Many research groups, institutions, and industrial companies have been developing various heat pipe cooled reactors for space and mobile application [1]. The heat pipe is a passive heat transfer device that operates based on the temperature difference and the cycle of evaporation, condensation, and capillary return of the working fluid without external power supply. The liquid metals have been widely adopted as the working fluids for space reactor heat pipes because the liquid metals possess high thermal conductivity, low viscosity, and thermal stability.

The Korea Atomic Energy Research Institute (KAERI) has been developing sodium heat pipes with hybrid wick for designing the space reactor [2, 3]. The hybrid wick is manufactured by double layered wick structures that sintered metal particles on the braided wick. The braided wick is adopted for fabricating bendable heat pipe, and the sintered wick is used to achieve higher capillary pressure.

The sodium heat pipe remains in a solid state at room temperature, and it starts operation with phase change phenomena above 500°C. As the temperature increases, heat losses via insulation increase; thus, it is essential to estimate the amounts of heat losses during startup operation. Notably, the substantial thermal energy required to heat up the insulation. The thermal inertia of insulation can lead to discrepancies in predicting the frozen startup behaviors and subsequent flow regime transitions of the sodium heat pipe.

In this study, numerical analysis related to the heat losses of a sodium heat pipe was conducted during the startup and continuum flow operation. A fundamental experiment study was conducted to identify the thermal behaviors of vertically installed sodium heat pipe installed hybrid wick.

2. Experimental Setup

The experiment apparatus was developed for thermal performance of individual heat pipe as shown in Fig. 1. The schematic diagram of sodium heat pipe and wick structure are depicted in Fig. 2.

2.1. Sodium Heat Pipe with Hybrid Wick

The heat pipe was fabricated with an outer diameter of 1/2 inch and a total length of 1.0 m. The material of container pipe was selected to stainless steel to ensure corrosion resistance and structural integrity under high temperature operating conditions. The specific dimensions are summarized in Table I.

2.2. Boundary Conditions for Experimental Apparatus

The experimental setup consists of an evaporator, adiabatic section, and condenser. The evaporator provides the radiation heating using two electrical heaters. The heaters are surrounded by insulation box to minimize heat loss to environment. The cylinder type insulation blocks were installed and metal foil wrapped on the blocks to limit the additional heat loss. The condenser was set to dissipate thermal energy via radiation and natural convection without cooling jacket.

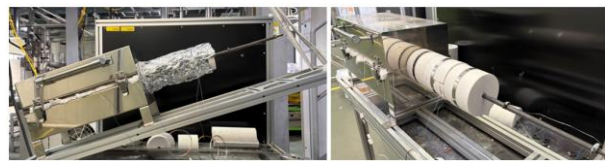


Fig. 1. Experimental apparatus for sodium heat pipe

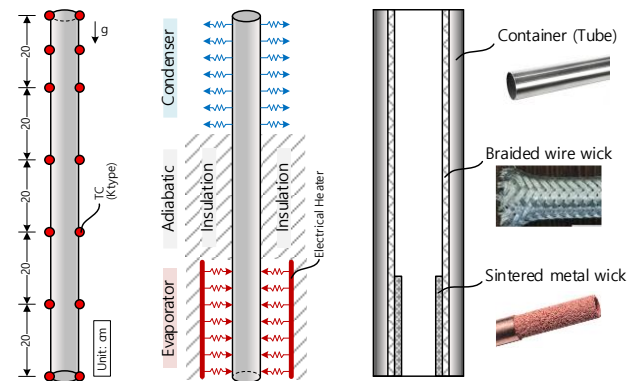


Fig. 2. Schematic Diagram of Heat Pipe and Wick Structure

Table I. Dimension of Sodium Heat Pipe

Parameter	Value
Working Fluid	Sodium
Materials	
- Container	Stainless Steel
- Braided wick	Stainless Steel
- Sintered wick	Stainless Steel
Radius (Inner / outer), mm	
- Container pipe	5.46 / 6.35
- Braided wick	4.36 / 5.46
- Hybrid wick	3.36 / 5.46
Length, m	
- Container pipe	0.25
- Braided wick	0.50
- Hybrid wick	0.25
Boundary condition, m	
- Evaporator	0.3
- Adiabatic duct	0.4
- Condenser	0.3

2.3. Instrumentation and Control Systems

An instrumentation and control system was established to monitor the heat pipe operation and to control the heater power. The K-type thermocouples were clamped to the outer surface of heat pipe to measure the real-time temperature distribution. The temperature signals were collected by a data acquisition (DAQ) system with a sampling time of 2 seconds. The two electrical heaters were installed independently allowing for independent control.

3. Heat Loss Estimation

3.1. Governing equations and methodology

In this section, the governing equations and numerical methodology to estimate the heat loss of the insulation box installed on evaporator section. The box is assumed to be cylindrical annulus geometry as depicted in Fig. 3. To analyze the heat loss of the insulation box, one dimensional transient heat conduction equation in cylindrical coordinates was formulated across the following three distinct domains.

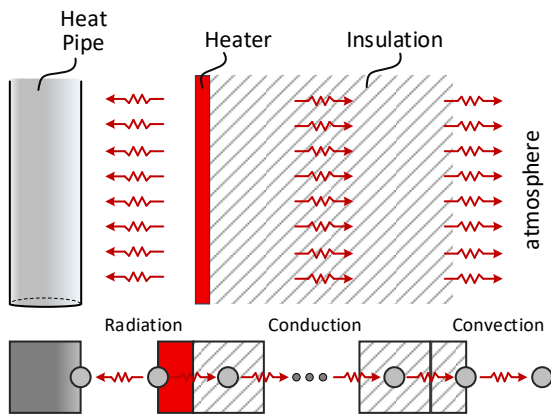


Fig. 3. Schematic diagram and nodalization for heat loss estimation of experimental apparatus

(1) Heat Pipe – Heater - Insulation Region

$$\rho c_p \frac{\partial T}{\partial t} = \frac{k}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) + q_{HT}''' - q_{HP}''$$

(2) Insulation Region

$$\rho c_p \frac{\partial T}{\partial t} = \frac{k}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right)$$

(3) Insulation - Atmosphere Region

$$\rho c_p \frac{\partial T}{\partial t} = \frac{k}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) - q_{Loss}''$$

where q_{HT}''' , q_{HP}'' , and q_{Loss}'' are stands for heat generation rate in a unit volume, heat flux to heat pipe, and heat flux to environment, respectively. The above equations were discretized using the finite difference method (FDM), and the implicit scheme was used to ensure both numerical stability and computational efficiency for transient analysis.

3.2. Conditions and Assumptions

The insulation has an outer radius of 20 cm. The heaters are assumed to be installed along the circumference with an inner radius of 3 cm in the insulation. The thermal energy is generated in the heater region, and the heat is transferred to the heat pipe by radiation with emissivity of 0.9 and the surrounding insulation by conduction. Commercial Superwool was used as the insulation material, with a density of 128 kg/m³, specific heat of 1,050 J/kg-K, and thermal conductivity of 0.22 W/m-K. The heat transfer coefficient of natural convection is assumed to be 10 W/m²-K and the ambient temperature is set to be 0°C. Ther surface temperatures of heat pipe to calculate the radiation heat transfer were used from experimental data at the 20 cm of the evaporator. The insulation domain was discretized into 20 nodes.

3.3. Analysis results

The results of the heat loss evaluation over time are presented in Fig. 4. The result shows that about 40-50% of total heater power was consumed to heat up the insulation for 1,000 seconds. The amount of thermal energy for heating the insulation decreases gradually because the additional temperature increases were limited by heat balance. The heat balance was maintained by the radiation to heat pipe and natural convection to atmosphere.

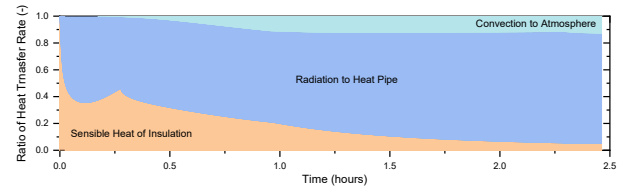


Fig. 4. Heater Power Consumption Ratio

The net heat transfer rate, subtracting the estimated heat losses from the measured heater power, is presented in Fig. 5. Approximately 270 W of thermal energy is transferred to heat pipe from 0 – 0.25 hours. This value gradually increases to 330W to 0.96 hours. Subsequently, the amount of heat transfer reaches at 987 W to 2.28 hours. The power supply was terminated at 2.466 hours.

4. Experimental results

In this section, the temperature changes over time and thermal characteristics of sodium heat pipe are described. The experimental results show the three distinct regimes based on temperature behaviors: frozen startup regime, geyser boiling regime, and continuum flow regime.

4.1. Frozen startup regime (0 – 0.5 hours)

At the beginning of the experiment, the electrical power was supplied to the heaters, the solid state of sodium undergoes a melting process. The temperature changes of adiabatic section and condenser remain extremely limited until the evaporator temperature reaches to approximately 500°C. When the evaporator temperature was above 500°C, the increasing rate becomes less steep. It was indicating the onset of phase change from liquid to vapor. The generated sodium vapor in evaporator migrates axially, and it results in the sharp temperature rise at 40 cm and 60 cm locations.

4.2. Geyser boiling regime (0.5 – 1.5 hours)

When the evaporator temperature reached approximately 600°C, the geyser boiling phenomena—characterized by periodic temperature oscillations—was observed. The geyser boiling occurred when the liquid pool was formed at the bottom of heat pipe, where bubbles were grown and rapidly ejected toward the upper sections periodically. The phenomena yielded intermittent sodium discharges through the vapor core, and it caused oscillatory behavior with periodic temperature spikes and subsequent drops in heat pipe surfaces. As the heater power increased, both the amplitude and period of these oscillations gradually diminished, and the vibrations eventually disappeared once sufficient power was applied.

4.3. Continuum flow regime (1.5 – 2.5 hours)

When the evaporator temperature rose sufficiently to approximately 700°C, the internal sodium flow reached a continuum flow regime. In this regime, the temperature distribution along the length of the heat pipe became uniform and approached isothermal condition. The experiment results showed that the heat pipe achieved an isothermal state with a temperature difference of less than 100°C, except for the end point of condenser (100 cm). The temperature of the 100 cm reached 400°C.

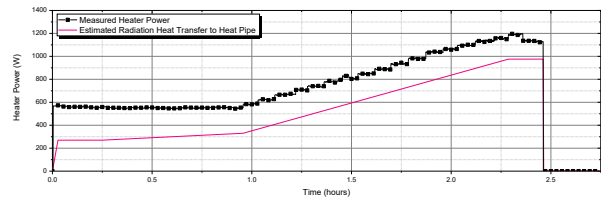


Fig. 5. Estimated Radiation Heat Transfer Rate to Heat Pipe

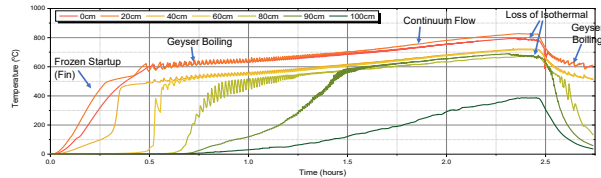


Fig. 6. Experimental Results of Individual Heat Pipe and its Hybrid Wick Structure

5. Conclusion

In this study, an experimental apparatus was established to evaluate thermal performance of individual sodium heat pipe. The amount of heat loss through the insulation box of evaporators was estimated by using FDM numerical analysis. Furthermore, the experimental study was conducted to evaluate the thermal performance of a sodium heat pipe with a hybrid wick in vertical mode. It was estimated that a substantial portion of electrical heater power was consumed to heat up the insulator for a while. When the enough preheating was conducted, most of the thermal energy transferred to heat pipe. Thus, the accurate estimation of heat loss is required to evaluate the frozen startup behaviors in the future. The typical thermal behaviors of regime transition from frozen startup regime, geyser boiling regime, to continuum flow regimes was observed with increasing the heater power. In the future, several studies will be conducted to simulate the observed phenomena using computation frameworks. In addition, the numerical models will be developed for the precise analysis of thermal behaviors of sodium heat pipes.

ACKNOWLEDGEMENT

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