A bendable liquid metal heat pipe: Numerical assessment and experimental validation

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1. Introduction

A bendable heat pipe is a key component for a fission surface power system [1]. Heat pipe transfers heat from the core to power conversion system without a gravitational assistance. Liquid metal in a heat pipe allows high temperature high heat flux operation. The bending capability is required for maximizing space utilization. A sterling converter is effective power conversion system in terms of payload and maintenance. As shown in Figure 1, Bendable heat pipes are applied for KAERI's heat pipe cooled reactor considering the space management.

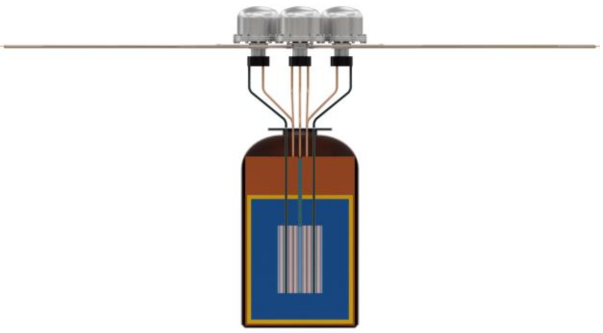

Fig. 1. Concept of KAERI's heat pipe cooled reactor for a fission surface power system

There are many types of conventional wicks, such as grooved, sintered powder and screen mesh, but these are not applicable to a bendable heat pipe. The bending capability is limited due to the deformation of wick structure. The deformed wick cause significant decrease in the heat transfer performance. We developed the hybrid structure with a sintered metal powder wick and braided wire wick for a bendable heat pipe. The braided wire wick was woven mesh with thin metal wires. Figure 2 shows the shapes of braided wire wick structure, which has good elasticity.

We proposed a novel design of a hybrid wick heat pipe for a heat pipe cooled reactor. A parametric study of the thermal performance of the heat pipes with different wick parameter was conducted via steady-state thermal performance calculation including operating limitations. We manufactured a sodium metal heat pipe and it was experimentally evaluated in terms of heat transfer performance.

Fig. 2. A schematic of braided wire wick

2. Methods and Results

2.1 Hybrid wick structure

Figure 3 shows the hybrid wick structure in a heat pipe. There are two layers of wick in the radial direction. The outer layer is a braided wire wick. It is flow path for liquid sodium. The inner layer is a sintered metal powder wick at the evaporator section. It provides capillary force for the operation of heat pipe. Both wicks were mechanically coupled without adhesive material.

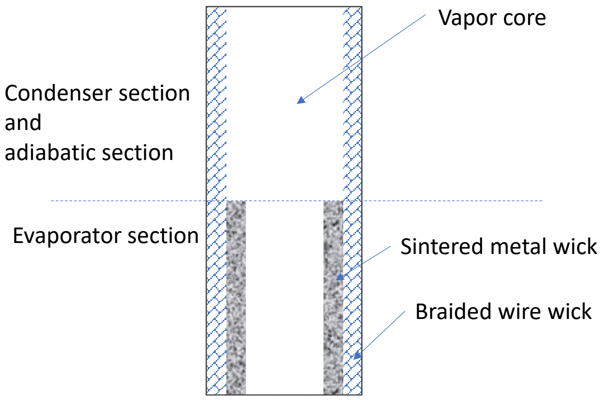

Fig. 3. Hybrid wick structure of the braided wire wick and the sintered metal powder wick

The material of the braided wire was stainless steel 316, which was braided using stainless steel wire with a diameter of 200 ㎛. The braided wire a forms annulus with the initial dimeter of 14 ㎜. The material of the sintered metal powder was stainless steel 316, and the median diameter of metal powder was 13.5 ㎛. The porosity and the pore diameter were measured as 38.7% and 4.8 ㎛, respectively. The measuring instrument was the Micrometrics AutoPore IV 9500.

2.2 Design of heat pipe

The total length was 1 m and the diameter of the heat pipe was 12.7 ㎜. The length of the evaporator section was 0.25 m.

The temperature distribution at the given operating condition was iteratively calculated with 0D steady-state thermal resistance model. Figure 4 shows thermal resistance circuit for the calculation. Heat transfer between vapors was not considered. The effective heat transfer coefficient between the power source and the outer surface of the heat pipe was assumed as infinite. Inlet temperature of the coolant was assumed to be 773 K and the effective heat transfer coefficient at the condenser was assumed to be 200 W/K. The capillary limit was also iteratively calculated by comparing the capillary force and the pressure drop at the operating temperature. Other operating limits were calculated after the iteration.

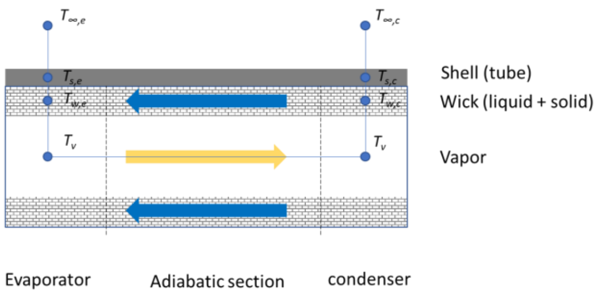

Fig. 4 Numerical model for design of a heat pipe

2.3 Experiments

The evaporator section was heated by the heating elements surrounding the heat pipe in the furnace. The condenser section was cooled by passive cooling through natural convection and radiative heat transfer. The operating limit was evaluated by estimating the heat removal rate through natural convection and radiative heat transfer on the surface of the condenser section. Figure 5 shows the experimental facility for measuring operating limit, as well as steady-state thermal performance

The length of evaporator, adiabatic, and condenser section were 0.25, 0.05 and 0.45 m, respectively

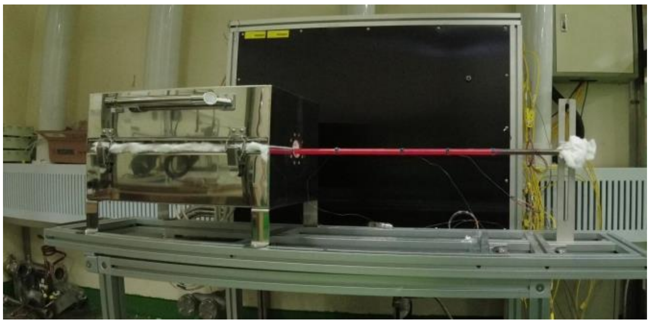

Fig. 5. Experimental facility for measuring operating limit

Figure 6 shows experimental facility for the transient test. The evaporator section was heated by the six heating elements, which were inserted in nickel block. The condenser section was cooled by air flow. The heat transfer through heat pipe was measured by the convective heat transfer at the condenser section. The entire components were installed in the furnace to prevent heat loss.

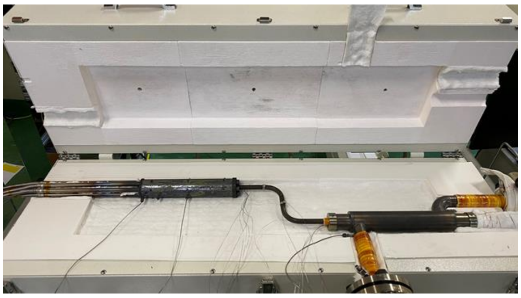

Fig. 6. Experimental facility for the transient test of a bended heat pipe

2.3 Code validation

KAERI developed computer code to predict the performance of heat pipe in a space reactor core. It is LUHPIS (Lumped Heat Pipe Simulator) code to simulate steady-state as well as transient operating condition for a heat pipe [2]. The experimental results were used for the validation of LUHPIS.

The input boundary conditions at the condenser for predicting the operating limit of the straight heat pipe was summarized in Table I.

Table I Boundary conditions at the condenser

Parameters	Value
Convective heat transfer coefficient (W/㎡-K)	15.75
Air temperature (℃)	16.0
Surface emissivity	0.758

2.3 Results

Figure 7 shows the experimental results for measuring operating limit of the straight heat pipe. As a result of additionally increasing the heater power, only the evaporator surface temperature increased, but the condenser surface temperature did not increase, which means that the manufactured heat pipe reached the operating limit.

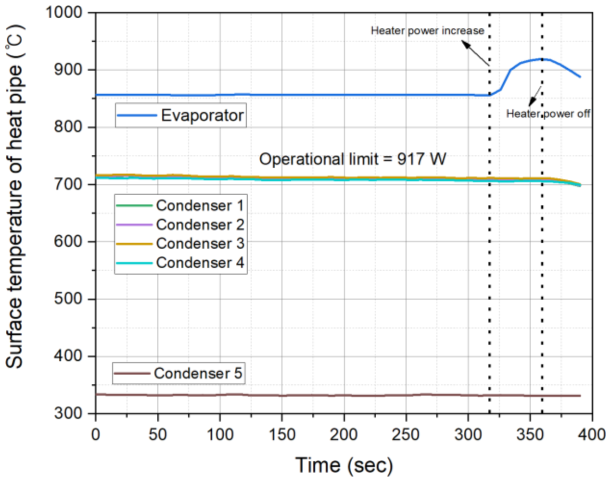

Fig. 7. Operating limit of the straight heat pipe

Table II shows LUHPIS calculation results which simulate the straight heat pipe. The minimum operating limit was entrainment limit and it showed good agreement with the experimental result. It was qualitatively expected that the operating limit was controlled by entrainment limit because the braided wire wick has a relatively large pore hydraulic radius among the conventional wick structures [3, 4].

Table II: Validation of operating limit

Calculation results	Value (W)
Viscous limit	15006
Sonic limit	2498
Capillary limit	31107
Entrainment limit	1012
Boiling Limit	350220
Experimental results (Entrainment)	917
Deviation	10.3 %

Figure 8 and 9 shows surface temperature distribution and heat transfer, which was measured by the convective heat transfer, of the bended heat pipe in the experiment. Data at 18,000 seconds were used for steady-state validation and data from 18,000 to 21,000 seconds were used for transient validation. The measured heat transfer data were used for time-dependent boundary condition at evaporator section in the code calculation. The boundary condition at the condenser section was time-dependent air flow rate and coolant air temperature.

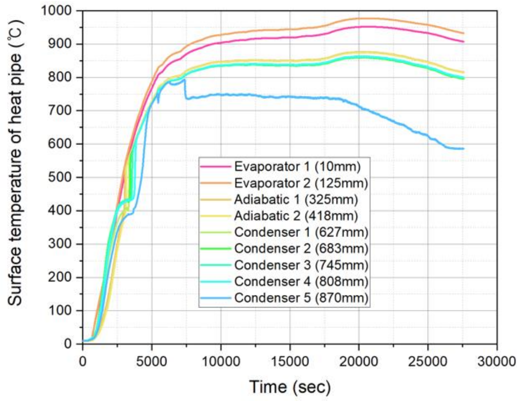

Fig. 8. Temperature distribution during the transient test

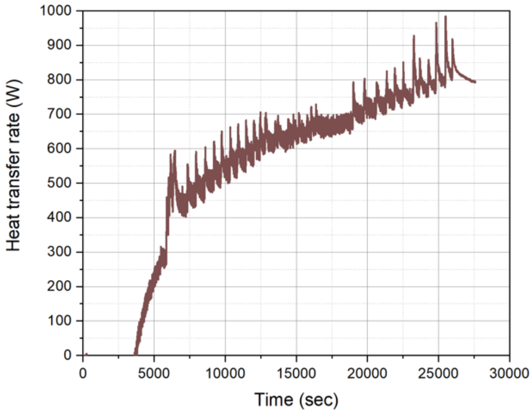

Fig. 9. Heat transfer during the transient test

Figure 10 shows surface temperature distribution during the transient test. LUHPIS code predicted the temperature of the adiabatic section within 1% of accuracy at the steady-state, which was from 18,000 to 18500 seconds. The code calculation results responded pretty sensitively to the heat from the evaporator section in comparison with experimental results. It shows good agreement within maximum 42 ℃ in terms of the surface temperature at adiabatic section.

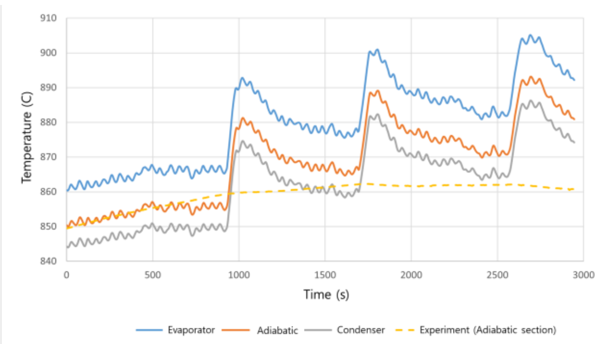

Fig. 10. Temperature distribution of the bended heat pipe during the transient test

3. Conclusions

In this study, we developed an approach to introduce a bendable heat pipe with a hybrid wick structure. The system consisted of a braided wire wick and a sintered metal powder wick. We measured the operating limit of the straight heat pipes on a target operating temperature. LUHPIS code predicted operating limit of the straight heat pipe quantitatively and qualitatively. We manufactured the bended heat pipe and measured thermal performance during transient. The steady-state and transient calculate capability of LUHPIS code was validated with the experimental data.

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