Parametric study of a high temperature heat pipe with hybrid wick structure

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1. Introduction

A heat pipe cooled reactor has been proposed for space purpose. NASA's Kilopower project targeted affordable fission nuclear power system for long-term operation on planetary surfaces [1]. The primary coolant is sodium heat pipe and the power conversion system is Stirling engine. The pros of the heat pipe cooled reactor is simplicity. Simple and long heat pipes transfer heat from the reactor core to power conversion system without turbomachinery. It is very cost effective in terms of payload and maintenance.

Conventional tubular heat pipes are straight but bendable heat pipes are required to maximize space utilization. Design and manufacturing of bendable heat pipes is a key challenge for space purpose. KAERI suggested the hybrid structure of braided wire wick and sintered metal powder wick for the bendable heat pipe as shown in Fig. 1. The braided wire wick provides the passage for the liquid flow. The sintered metal wick provides the capillary force with minimizing the pressure drop. Characteristics of the braided wire wick was evaluated in the previous study [2]. The hybrid wick structure is a unique feature and it is not standardized. Therefore, parametric study of the wick elements of the bendable heat pipe is needed to optimize the design.

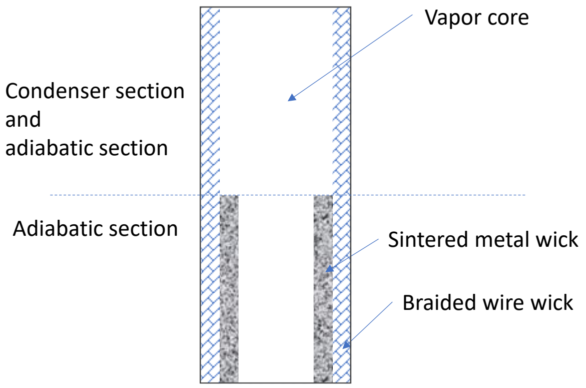

Fig. 1 hybrid structure of braided wire wick and sintered metal powder wick

In the present study, parametric study of the sodium heat pipe with the hybrid wick structure was conducted. The operational limits were calculated with changing parameters of the hybrid wick structure.

2. Material and methods

This section describes the operating condition and components of the heat pipe and method of parametric analysis.

2.2. Operating condition

The target operating temperature was 750 ℃. Effective heat transfer coefficient between power source and the outer surface of the heat pipe was assumed as infinite. Inlet temperature of coolant was assumed to be 773 K and effective heat transfer coefficient at condenser was assumed to be 200 W/K.

2.2. Components of the heat pipe

The working fluid was sodium. Material of the container tube was stainless steel 304. The outer diameter was 12.7 ㎜ and the wall thickness was 0.89 ㎜. The wick of condenser and adiabatic part was braided wire wick. The dimension of braided wire wick is described in Table I. At evaporator section, sintered metal wick was positioned inside the braided wire wick. Both wicks are mechanically coupled. The outside of the braided wire wick is the tube.

Table I Dimension of the braided wire wick

Material	SS 304
Diameter of wire (㎛)	200
Outer diameter (㎜)	12.8
Inner diameter (㎜)	10.6
Wick thickness (㎜)	1.1
Porosity	0.805

Material of sintered metal power was stainless steel 304.

Permeability of braided wire wick was calculated by Blake-Kozey equation [3,4]:

$$K = \frac{d_{wire}^2 \varepsilon^3}{122(1-\varepsilon)^2} \qquad (1)$$

2.3. Parameters

Three parameters were selected for the parametric study. The common operational limit of sodium heat pipes over 700 ℃ were capillary limit and entrainment limit. Parameters in Table II affects capillary force, pressure drop, and entrainment. Bold value in the table was default value. The maximum capillary pressure, P_{cm} , is defined as:

$$P_{cm} = 2\sigma / r_c \tag{2}$$

where σ and r_c are the surface tension coefficient of the liquid and the effective capillary radius, respectively. It is defined in the sintered metal power wick as [5]:

$$r_c = 0.41 r_s, r_s = \text{particle radius} \tag{3}$$

The general equation for the capillary limitation on heat load for heat pipes in a zero gravitational field is:

$$\frac{2\sigma}{r_c} = \int_{x_{min}}^{x_{max}} \left(\frac{dP_v}{dx} - \frac{dP_l}{dx}\right) dx \tag{4}$$

where subscription v and l are vapor and liquid, respectively. The conservation of momentum requires following fluid pressure gradient terms as:

$$\frac{dP_v}{dx} = -F_v Q - D_v \frac{dQ^2}{dx} \tag{5}$$

$$\frac{dP_l}{dx} = -F_l Q \tag{6}$$

where Q, F_v, D_v are the heat load, the frictional pressure coefficients and the dynamic pressure coefficients for the vapor flow.

Table II Parameters affecting operational limits

Braided wire wick	
Diameter of wire (μm)	50, 100, **200**
Sintered metal wick	
Radius of particle (μm)	**20**, 50, 100
Thickness of wick (mm)	0.1, **0.5**, 1.0

The common expression for the entrainment heat transport limit is [5]:

$$Q_{e,max} = A_v \lambda \left(\frac{\sigma \rho_v}{2 r_{h,s}}\right)^{1/2} \tag{7}$$

where ρ_v and $r_{h,s}$ are the vapor density and the surface pore hydraulic radius. The entrainment limit, $Q_{e,max}$, is proportional to the production of the vapor core cross-sectional area A_v and the latent heat of vaporization λ.

The surface pore hydraulic radius of the braided wire wick was assumed as the hydraulic radius of the open groove because the data for the braided wire wick is absent. This radius is equal to the width of the groove for groove wicks. The spacing in braided wire wick was assumed to be diameter of wire in Fig. 2.

$$r_{h,s} = w, w = \text{wire spacing} \tag{8}$$

$$w = D, D = \text{diameter of wire} \tag{9}$$

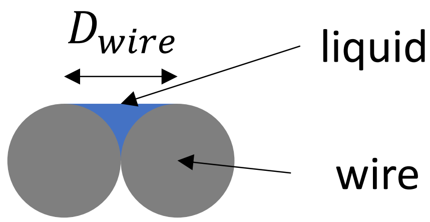

Fig. 2 Assumption for surface pore hydraulic radius of the braided wire wick

2.4. Calculation

The operational limit calculation was conducted with 0D steady-state thermal resistance model. Figure 1 shows thermal resistance circuit for the calculation. Heat transfer between vapors was not considered

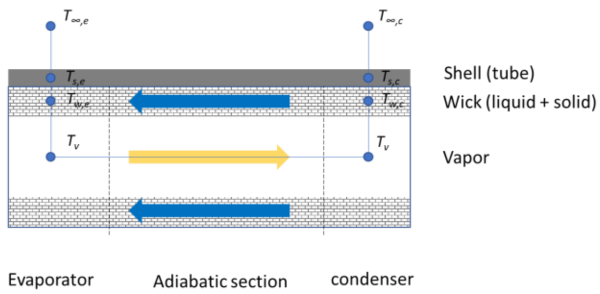

Fig. 3 Heat transfer through a heat pipe

3. Results

Operational limit calculations with change in diameter of braided wire are summarized in Table III. The radius of the sintered particle was 20 ㎛ and the thickness of the sintered wick was 0.5 ㎜. Those values were default value.

Entrainment limit is lower than capillary limit in every cases. The operational limit mainly is controlled by entrainment limit. The thermal performance of the heat pipe is enhanced to use thinner braided wire. Thinner wire decreases the porosity of the braided wire wick structure and it increases the pressure drop.

Table III Operational limits with changes in diameter of braided wire

Diameter of wire (μm)	Capillary limit (W)	Entrainment limit (W)
50	6300	2196
100	6960	1553
200	7138	1098

Operational limit calculations with change in radius of sintered metal particle are summarized in Table IV. Capillary force decreases as the radius increase. The pressure drop in the fluid is almost the same. The operational limit is controlled by the minimum value, entrainment limit.

Table IV Operational limits with changes in radius of sintered metal particle

Radius of particle (㎛)	Capillary limit (W)	Entrainment limit (W)
20	7138	1098
50	4330	1098
100	2954	1098

Operational limit calculations with change in the thickness of sintered metal wick are summarized in Table V. The thickness effect was negligible. There is a practical limit for the thickness of the sintered wick due to the machining technique of sintered metal. The thicker sintered wick is easy to process and gives solid structural integrity.

Table V Operational limits with changes in thickness of sintered metal wick

Thickness of wick (㎜)	Capillary limit (W)	Entrainment limit (W)
0.1	7138	1098
0.5	7125	1098
1.0	7110	1098

4. Conclusions

The operational limits of sodium heat pipes with hybrid wick structure, composed of braided wire wick and sintered metal wick, were calculated. The operational limit was mainly controlled by entrainment limit at given operational condition. The diameter of braided wire was a key parameter to enhance the thermal performance. The radius of sintered metal particle affects capillary force. The effect of the thickness of sintered metal wick was negligible.

Acknowledgement

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