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3D printed heat pipe design for space nuclear reactor application

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1. Introduction

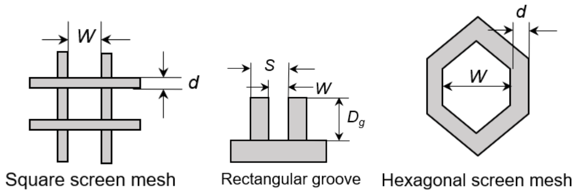
The passive two-phase heat transfer device, heat pipe, transports heat from the heat source to heat sink with capillary pumping force and phase change of the working fluid. The heat pipe has been applied as a thermal control system of satellites and spacecraft due to its high efficiency of heat transfer performance in zero gravity, structural simplicity, and passive heat transport without external power. To apply heat pipe as a passive heat transfer system, design optimization of heat pipe should be conducted because the thermal performance of the heat pipe can be varied according to the various design factors.

Heat pipe consists of an evaporator, adiabatic, and condenser sections where the working fluid evaporates in evaporator and vapor travels to condenser. After the heat release in condenser, condensed working fluid transported back to evaporator section by capillary pumping force. The thermal performance of the heat pipe can be determined by various design parameters. In particular, the factors governing the heat transfer capacity of the heat pipe is capillary pumping force which is driving force of the working fluid circulation which in turn determines the maximum heat transfer capacity, the wick is a key component that significantly influences the performance of the heat pipe because it provides a path for the working fluid to transport from condenser to evaporator by capillary pumping force. For enhanced heat transfer capability, optimal wick structure should be selected to achieve the maximum driving force of heat pipe.

In this study, design optimization of heat pipe wick structure will be performed with screen wire mesh – groove combined wick structure to overcome the homogenous wick type. 3D-printed heat pipe test section will be used to fabricate different types of wick structure heat pipe and conduct the experiment to evaluate the thermal performance enhancement of combined wick compared to the homogenous wick structure.

2. Design characteristics of heat pipe wick structure

2.1 Design factors of heat pipe wick structure



Square screen mesh
Rectangular groove
Hexagonal screen mesh

Fig. 1. Design parameters for different wick types

Table I: Design factor calculation for homogenous wick [2].

	Screen mesh	Groove wick
Effective pore radius	$\frac{W+d}{2}$	W
Porosity	$1-\frac{1.05\pi Nd}{4}$	$\frac{W}{S}$
Hydraulic diameter	$\frac{d\varphi}{1-\varphi}$	$\frac{4D_gW}{(2D_g+W)}$
Permeability	$\frac{d^2\varphi^3}{122(1-\varphi)^2}$	$\frac{D_h^2\varphi}{2(f\,\mathrm{Re}_{l,h})}$
Thermal conductivity	$\frac{(Lk_sk_lD_g)+(Wk_l)(0.185LK_s+D_gk_l)}{(W+L)(0.185LK_s+D_gk_l)}$	$k_l\frac{(k_l+k_s)-(1-\varepsilon)(k_l-k_s)}{(k_l+k_s)+(1-\varepsilon)(k_l-k_s)}$

The wick structure within the heat pipe, the small pore size is required at the vapor-liquid interface to develop high capillary pumping force, and a large pore size is preferred for less resistance in flow movement. [2] There are three design factors important for wick structure selection: effective pore radius, permeability, and thermal conductivity. (Fig. 1, Table. I.) For smaller effective pore radius, larger capillary pumping force can be induced from wick structure but has lower permeability due to larger flow resistance. The wick can be categorized as a homogeneous wick (artery, sintered powder, screen wire mesh, groove) and composite wick which combines homogenous wicks. Each homogenous wick type has advantages and limitations. For example, screen mesh wick has a relatively small effective pore radius which enables the generation of large capillary pumping force but has large fluid flow resistance which results in low permeability. On the other hand, the groove wick has a large effective pore radius but also a large permeability that can transport working fluid over a long distance. Therefore, achieving high capillary pumping force and high permeability cannot be satisfied at the same time for homogenous wick structure. To

Table II: Design parameters for 3D-printed combined wick

Parameter		**Value**
Material		SS316
Pipe OD/ID (mm)		25.4/22.0
Pipe length (mm)		200
Groove wick	Number	40
	Depth (mm)	2.5
	Width (mm)	0.85
	Fin thickness (mm)	0.8
Hexagonal screen mesh	Width (mm)	0.5
	Thickness (mm)	0.3

Table. III. Design factors investigation according to the wick structure type.

	Screen mesh	Groove wick	Groove-hexagonal screen mesh
Effective pore radius [mm]	0.4	0.53	0.4
Porosity (φ)	0.67	0.48	0.48
Hydraulic diameter (D_h) [mm]	0.21	1.27	1.27
Permeability (K) [m^2]	9.60×10^{-10}	4.28×10^{-8}	4.28×10^{-8}
Thermal conductivity (k) [W/m-K]	1.26	4.03	4.03

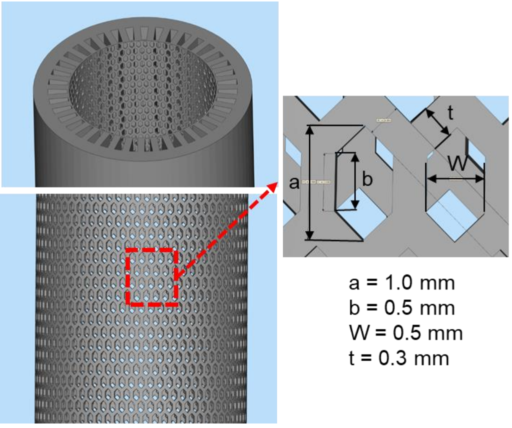


Fig. 2. 3D printed combined heat pipe wick configuration

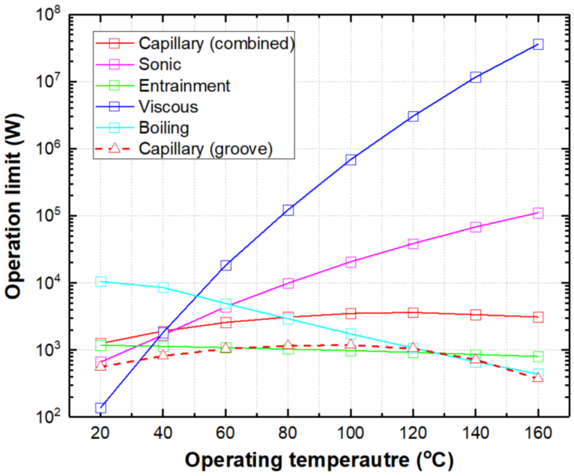


Fig. 3. Operation limit comparison of combined wick and groove wick.

overcome the limitation of homogenous wick performance, a combined wick structure was considered for space nuclear reactor application.

2.2 Design of combined wick structure

To use heat pipe for space nuclear reactor application, heat pipe must be operated in zero gravity condition driven by capillary forces occurred in the wick. Applying homogenous wick has different limitations for each type such as lack of capillary pumping force or permeability. Therefore, in this study, combined wick structure with groove wick and screen mesh wick was considered for heat pipe design optimization for space nuclear reactor application by investigating important wick design factors.

Screen wire mesh was adopted for enhanced capillarity by reducing effective pore radius and increase evaporation rates by adding several layers on top of a wide groove wick with large pore size. Also, groove wick beneath the screen wire mesh wick can supplement the limitation of screen wire mesh which has large flow resistance by providing extra working fluid flow path and pool under the evaporation sites. When applying heat pipe to space nuclear reactor, it should be bent to prevent contact with Stirling engine, where the application of the groove wick can prevent damage of the wick structure due to bending. Evaporator wick design with screen mesh and groove wick can overcome the limitation of the homogenous wick with enhanced capillary force, permeability, evaporation performance and advantage in fabrication of bended heat pipe at the same time.

Sophisticated fabrication of complex combined wick structure will be fabricated using 3D printing. For easier and solid fabrication with powder stacking 3D printing, screen mesh geometry was selected as hexagonal shape as shown in Fig. 2. Also, by fabricating complex evaporator wick using 3D printing, distortion can be prevented in connected parts between screen wire mesh and groove wick and reduce contact thermal resistance.

The proposed hexagonal screen wire mesh and groove combined wick design parameters are listed in Table. II. With suggested design parameters, important design factors of wick structure were calculated and compared with the homogenous wick. (Table. III.) Overall, the combined wick structure can achieve larger capillary pumping force and permeability at the same time, overcome the limitation of homogeneous wick.

To evaluate the combined wick heat pipe performance preliminary to the experiment, operation limit was investigated. (Fig. 3) With smaller effective capillary radius of combined wick evaporator section compared to groove wick, the capillary limit was enhanced for overall operating temperature range. However, in 70-130°C temperature range, heat pipe performance is stil limited by entrainment limit, so additional enhancement should be considered to enhance entrainment limit by adjusting wick thickness.

3. 3D printed heat pipe fabrication for Space nuclear reactor application

To use heat pipe as a heat transport system for space nuclear reactor, design optimization should be achieved for higher efficiency and compact reactor design by selecting the proper working fluid or geometry. As shown in Fig. 4., the heat pipe cooled space nuclear reactor is composed of a core, power conversion system, radiator, and heat pipe that connects each system. To avoid the contact between heat pipe and power conversion system or radiator, heat pipe has bended shape, and heat transfer area of heat pipe evaporator or condenser has different geometry from conventional heat pipe (Fig. 5). During the bending process, a capillary wick structure located inside the heat pipe wall can be distorted and separated from the inner wall which can disturb working fluid circulation and eventually deteriorate the thermal performance of the heat pipe. Also, the complex geometry of an evaporator should be designed to effectively deliver heat from core to power conversion system cold side by achieving maximum heat transfer area. 3D printing technique can overcome the problem with conventional fabrication process of bended heat pipe and complex wick structure to apply for space nuclear reactor heat transport system. For example, groove wick of heat pipe is usually fabricated on flat plane and rolled into cylindrical shape which is hard to fabricate constant width groove and cannot easily bended due to groove distortion and pipe wall thickness change. Although the combined wick can significantly enhance the capillary force, due to its high manufacturing costs and difficulty, usage of homogenous wick was preferred. Using 3D-printing technique, it is possible to produce complex wick geometry more easily as a single unit with constant thickness and avoid the assembly of the different parts which can induce damage in high pressure condition or during construction. (Fig. 6) Also, flexible evaporator design can be performed to achieve maximum heat transfer area between heat pipe condenser and heat sink.

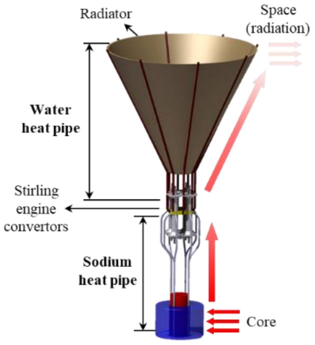


Fig. 4. Concept of heat pipe cooled space nuclear reactor

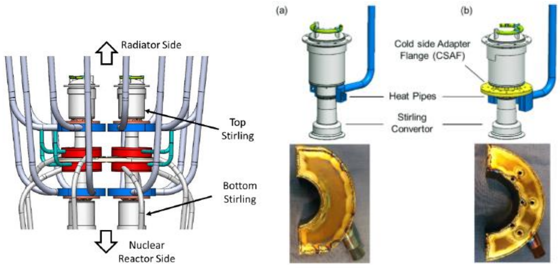


Fig. 5. Connection of heat pipe and cold side of power conversion system. (Kilopower, NASA) [1]

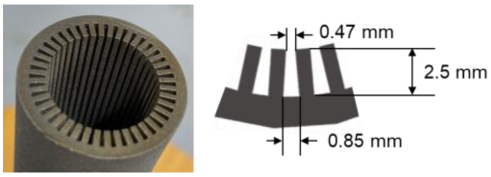


Fig. 6. 3D-printed groove wick

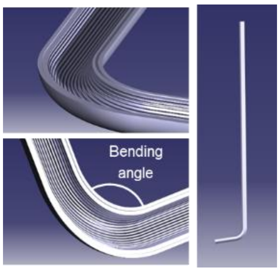


Fig. 7. Bended heat pipe geometry with 3D-printing.

Fabrication of heat pipe with no distortion or damage in wick during bending process is also possible to apply heat pipe to space nuclear reactor cooling system as shown in Fig. 7.

4. Experimental Setup

An experimental study will be performed to evaluate the thermal performance of heat pipe with 3D printed combined wick. Heat pipe test sections for various wick

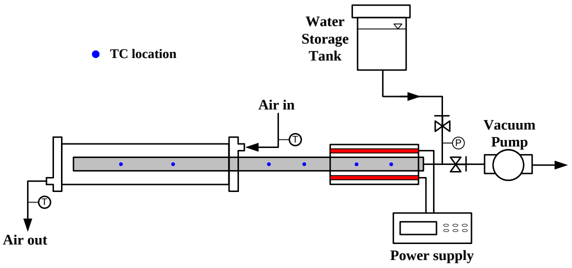


Fig. 8. Schematic diagram of heat pipe experimental setup.

Table. IV: Heat pipe experimental conditions.

Parameters	**Value**
Pipe material	SS316L
Working fluid	Water
Fill ratio (%)	100
Length ratio (evp:adi:con)	1:1:2
Heat load (W)	50-300
Orientation	Horizontal

structure were fabricated with metal 3D-printing. Due to the 3D printer limitation, three different parts of heat pipe with groove wick or groove-screen will be fabricated separately and assembled by welding. Total length of the heat pipe test section is 0.8 m long with 25.4 mm diameter. For performance comparison according to the wick combination, wick structure for evaporator, adiabatic and condenser section will be assembled with different types with combination of groove, screen mesh, and groove-hexagonal screen mesh wick.

The 3D printed heat pipe experimental setup consists of six cartridge heaters, DC power supply, air cooling jacket as shown in Fig. 8. To measure the wall temperature of the heat pipe, K – type thermocouple will be installed along the test section. To conduct the heat pipe performance experiment, first, input power to evaporator until the working fluid inside the heat pipe sufficiently heated and evaporated. Then, apply cooling with compressed air to remove the heat from condenser section and circulate the working fluid through condenser to evaporator. After steady-state of wall temperature was achieved, apply different heat input for each step. The detail experimental conditions are listed in Table. IV.

5. Summary and Further plan

To apply heat pipe to space nuclear reactor thermal control system, design optimization was performed using 3D-printed combined wick heat pipe fabrication. Enhanced wick design factors were achieved by adopting combined screen wire mesh and groove wick in evaporator section with enhanced evaporation rates and permeability. Several performance factors such as effective pore radius, permeability, and thermal conductivity of combined wick were compared with a homogenous wick to investigate the enhanced capillary wick characteristics. 3D printing technique enables to fabricate complex combined wick with easier manufacturing process and sophisticated fabrication. The thermal performance of 3D printed combined wick heat pipe will be evaluated experimentally and compared with homogenous wick structures for further work.

ACKNOWLEDGEMENT

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