Design Study of Hybrid Wick Structure for Enhanced Thermal Performance of Heat Pipes in Spaceship Applications

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1. Introduction

A heat pipe is a passive heat transfer device driven by phase change and capillary pumping pressure which has advantages for high effective thermal conductance, zero gravity operation, passive cooling and light weight. The working fluid heated at the evaporator section and after vapor flows to the condenser section, condensed fluid transported to evaporator through porous medium in wick structure of heat pipe which induce capillary pumping pressure between the evaporator and condenser sections as shown in Fig.1. A heat pipe is used in many engineering fields especially in space nuclear reactors to remove the high heat capacity in absence of gravity and pumping power.

To improve inherent stability and develop a safety system for use of nuclear power as a power source in space, many design concepts of micro heat pipe cooled reactor for space application were developed. NASA is developing small fission power system, Kilopower, to operate from 1 to 10kWe for space application since 2015.[1] Kilopower consists of two types of heat pipe which use sodium and water as a working fluid for heat transport device between reactor core, Stirling engine, and radiator as shown in Fig. 2. To operate heat pipes for space application, working fluids in heat pipe should be able to return from condenser to evaporator in zero gravity, micro gravity for space condition operation and gravity-assisted orientation for ground testing. In order to satisfy the operation conditions in space, design of heat pipe wick structure is very important to overcome the pressure losses occur in pipe and operate in zero gravity condition. Therefore, several wick structures were suggested for space nuclear reactor heat pipes.

In this paper, the design study of hybrid wick structures of heat pipes for space nuclear reactor application and enhancement in heat transfer capacity is conducted in terms design factors and operation limits is performed.

2. Designing hybrid wick structures

2.1 Hybrid wick structure

Since the thermal performance of the heat pipe is affected by various design parameters, selecting optimal design for operating in both space and ground condition is important. There are several design properties that must be considered for heat pipe design. Minimum capillary radius for large capillary pressure difference, large permeability to have a small liquid pressure drop, and large effective thermal conductivity for small temperature drop across the wick. However, it is hard to satisfy all the three properties at the same time, therefore make trade-offs between these design factors to obtain an optimal wick design is important. [2]

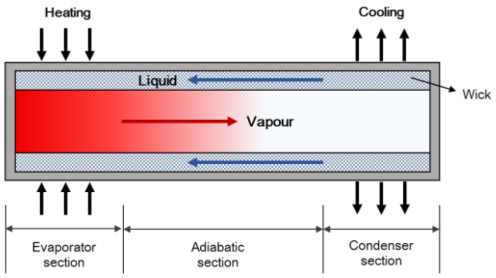

Fig. 1. Structure of heat pipe.

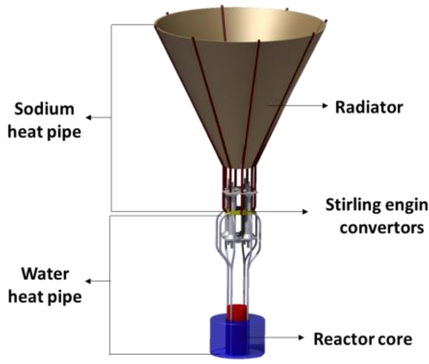

Fig. 2. Concepts of Kilopower with heat pipes.

Among several homogenous wick structures, grooved wick which has very high permeability was considered which allowing very long heat pipes for operation in micro gravity for space application. However, due to the large capillary radius, it has limitation for low pumping capability. Therefore, Ababneh et al. [3] suggested hybrid groove-screen wick structure which has a porous wick in evaporator, and a grooved wick in the adiabatic and condenser sections to operate in against gravity condition and carry power for long distance. (Fig. 3)

2.2 Capillary limit

The heat pipe has operating limits for the maximum heat transport capacity such as capillary limit, viscous limit, entrainment limit, sonic limit and boiling limit, which is determined by various design factors such as

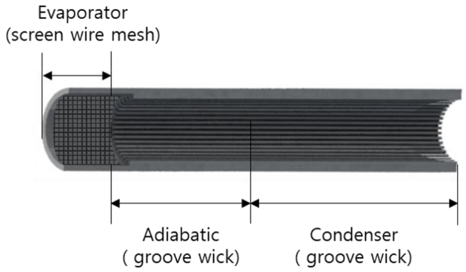

Fig. 3. Cross section of hybrid groove-screen mesh wick structure.

working fluid properties, wick structure, or operating conditions. [4] Typically, the capillary limit determines the maximum heat transfer capacity of the heat pipe over much of the operating range. In order to operate the heat pipe, the maximum capillary pumping pressure, $P_{cap,max}$, must be greater than the total pressure drop in the pipe as described in equation (1). The left-side term is the maximum capillary pumping pressure which occurs in evaporator section, and the right-side terms are viscous pressure losses in vapor, inertial and viscous pressure losses in liquid, normal and axial hydrostatic pressure losses.[4]

$$\frac{2\sigma}{r_{ce}} \geq \left(\frac{f_v \,\mathrm{Re}_v\, \mu_v}{2r_{hv}^2 A_v \rho_v \lambda} L_{eff}\, q\right) + \left(\frac{\mu_l}{K A_w \lambda \rho_l} L_{eff}\, q\right) + \left(\rho_l g d_v \cos\psi\right) + \left(\rho_l g L_{eff} \sin\psi\right) \qquad (1)\ [4]$$

So, the capillary limit can be expressed as

$$q_c = \frac{\dfrac{2\sigma}{r_{ce}} - \rho_l g d_v \cos\psi - \rho_l g L_{eff} \sin\psi}{\left(\dfrac{f_v \,\mathrm{Re}_v\, \mu_v}{2r_{hv}^2 A_v \rho_v \lambda} + \dfrac{\mu_l}{K A_w \lambda \rho_l}\right) L_{eff}} \qquad (2)\ [4]$$

Since the wick structures of the evaporator and the adiabatic, condenser sections are different, the properties of each wick structure were reflected using L_{eff} term which is sum of the length of evaporator, adiabatic and condenser as described in equation (3) and (4).

$$L_{eff} = \frac{L_e}{2} + L_a + \frac{L_c}{2} \qquad (3)$$

$$q_{cap} = \frac{\dfrac{2\sigma}{r_{ce}} - \rho_l g \cos\psi\, d_v - \rho_l g \sin\psi \left(\dfrac{L_e}{2} + L_a + \dfrac{L_c}{2}\right)}{\left(\dfrac{f_v \,\mathrm{Re}_v\, \mu_v}{2r_{hv}^2 A_v \rho_v \lambda} + \dfrac{\mu_l}{K A_w \lambda \rho_l}\right)\left(\dfrac{L_e}{2} + L_a + \dfrac{L_c}{2}\right)} \qquad (4)$$

As the local liquid-vapor pressure difference approaches to zero at the condenser end, capillary radius of evaporator section was used for maximum capillary pressure term in capillary limit calculation.

$$P_{cap,\max} = \frac{2\sigma}{r} \qquad (5)$$

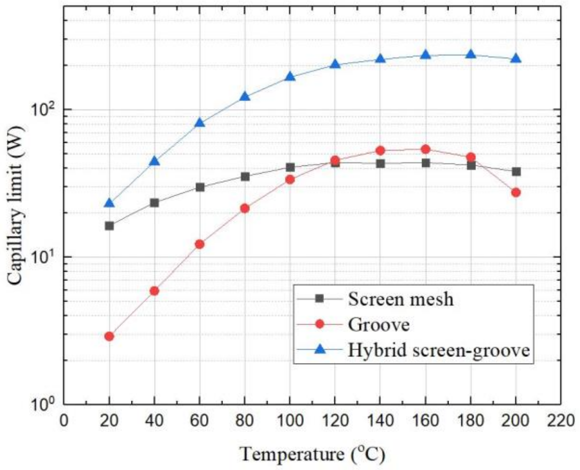

Fig. 4. Comparison of capillary limits for homogenous and hybrid wick structure.

Table I: Test matrix for hybrid groove-screen mesh wick capillary limit calculation

Parameter		**Value**
Pipe	O.D / I.D (mm)	25.4 / 22
	Length (cm)	100 (evp:adi:con = 27:68:5)
	Tilt angle (°)	Horizontal
Wick structure	Evaporator	Screen wire mesh (100-mesh, SS304)
	Adiabatic, Condenser	Axial groove wick (46 grooves)

With equation (4) and test matrix describe in Table I, the capillary limit of hybrid groove - screen mesh wick structure was evaluated as shown in Fig. 4. Test matrix of hybrid wick structure was optimized by comparing the effects of capillary radius, permeability and effective thermal conductivity in terms of design factors such as number of grooves or mess. The capillary limit of hybrid groove-screen mesh wick enhanced compared to homogenous wick structures. By applying different wick structures in evaporator and adiabatic, condenser section as shown in Fig. 3, capillary limit will be enhanced due to increased capillary pumping pressure with small pore size in evaporator, and increased permeability with grooved wick in adiabatic and condenser section.

For further hybrid wick heat pipe experiment, capillary limit of heat pipe with two types of screen mesh wick in evaporator and adiabatic, condenser section was also evaluated in horizontal orientation as shown in Fig. 5. By applying fine mesh in evaporator section, and coarse screen mesh in adiabatic, condenser section, the capillary pumping pressure and permeability will be increased which lead to the enhancement of capillary limit compared to homogenous screen mesh wick.

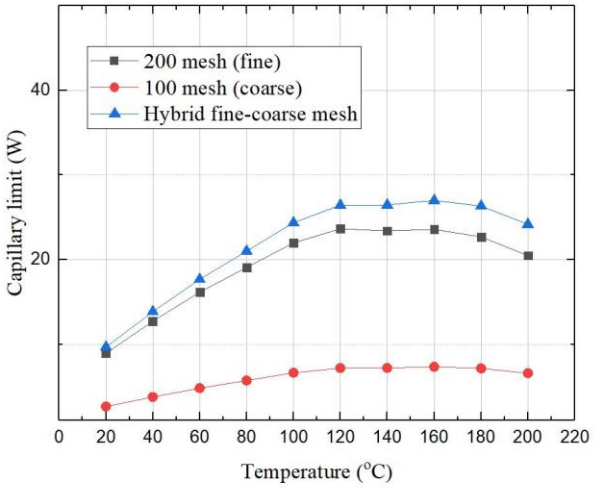

Fig. 5. Comparison of capillary limits for homogenous screen mesh wick and hybrid fine-coarse screen mesh wick.

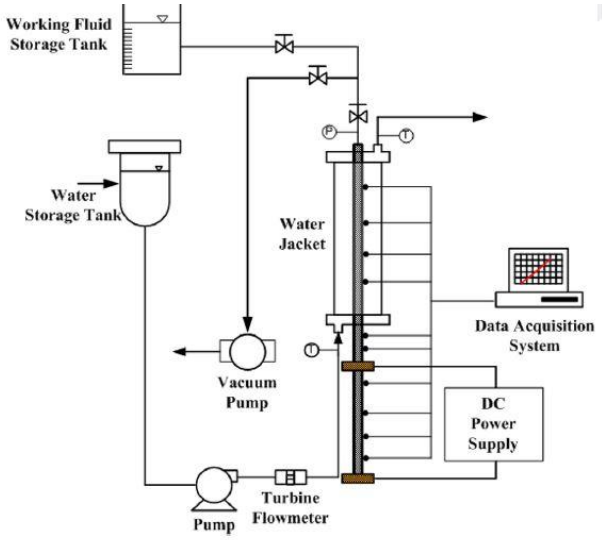

Fig. 6. Schematic diagram of Ulsan National Institute of Science and Technology heat pipe test facility. [5]

3. Experimental setup

The test facility consists of a test section, a water jacket, a working fluid tank, a pump, a vacuum pump, and two copper electrodes in evaporator section. (Fig. 6) [5]. A 1-m long stainless steel 316L pipe with 25.4 mm outer diameter and 22 mm inner diameter will be used as the test section. The length ratio of sodium heat pipe in Kilopower was referred for test matrix of experiment. For hybrid wick heat pipe, different types of screen mesh will be used. Fine screen mesh in evaporator for large capillary pumping pressure and coarse screen mesh in adiabatic, condenser section for large permeability. The effect of the mesh number difference will be estimated by adjusting mesh number difference between evaporator and adiabatic, condenser section.

The experiment will be performed in both horizontal, and slight adverse gravity orientation for space condition application.

Table II: Test matrix of hybrid fine-coarse screen mesh wick heat pipe experiment

Parameter		**Value**
Length ratio (%)		evp:adi:con = 4:9.7:1
Tilt angle		Horizontal, slight adverse gravity
Wick structure	Evaporator	100-400 screen mesh
	Adiabatic, Condenser	200-500 screen mesh

3. Summary and Further works

In this paper, design study of wick structure of heat pipes was performed through evaluate the design factors and capillary limit to derive optimal design for high heat transfer capability for space nuclear reactor application. Enhancement of capillary limit of hybrid wick was observed compared to the homogenous wick structure. The experiment with hybrid wick structure by varying several operation conditions and design factors will be performed to estimate the heat transfer capacity and capillary limit and optimization of design of hybrid wick structure will be conducted based on the experimental results.

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NOMENCLATURE

A	area
P	pressure
Re_v	Reynolds number of vapor
T	temperature
K	permeability of the wick
L_{eff}	effective length of the pipe

Greek-letters

σ	surface tension
μ	viscosity
ρ	density
λ	latent heat off vaporization
ψ	tilt angle

Subscripts

c	condenser
e	evaporator
g	gravity
r	capillary radius of wick
q	heat transfer rate

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