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Study of Diameter Variation Affecting the Thermal Performance of Heat Pipe for Space Nuclear Reactor Applications.

Ye Yeong Park, In Cheol Bang *
Department of Nuclear Engineering, Ulsan National Institute of Science and Technology (UNIST)
50 UNIST-gill, Ulju-gun, Ulsan, 44919, Republic of Korea
**Corresponding author: icbang@unist.ac.kr*

1. Introduction

The application of heat pipes as passive thermal control devices has been considered and successfully used in various engineering fields such as electronic devices or spacecraft. A heat pipe is driven by capillary pumping force and phase change of the working fluid and consists of an evaporator and adiabatic and condenser sections. Working fluid inside the heat pipe evaporates as the heat input at the evaporator from the heat source and vapor moves to the condenser and releases the heat into the heat sink. Then, the condensed working fluid is transported back to the evaporator by capillary pumping force, as shown in Fig. 1.

The advantages of using heat pipes in thermal control systems include high heat transport capacity, zero gravity operation, structural simplicity, and light weight. [1] With such advantages, applying heat pipe in nuclear reactor has been considered to improve the stability, simplified reactor design, and prevent single point failure accidents by preventing core damage, self-containment and heat removal from the reactor core passively and continuously after the shutdown. Therefore, the various concepts of heat pipe cooled reactor were developed especially for space nuclear reactors. As shown in Fig. 2, the heat pipe cooled space nuclear reactor consists of the core, power conversion system, radiator to release residual heat to surroundings, and heat pipes to transport heat from core to power conversion system, or through the radiator. [2] Several concepts of heat pipe cooled nuclear reactor was developed such as 15-kW HOMER (Heatpipe-Operate Mars Exploration Reactor) developed by the Los Alamos National Lab [3], or 111-kWe SAIRS (Scalable AMTEC Integrate Reactor Space Power Systems) which employ fast-spectrum reactors cooled by sodium and potassium heat pipes [4]. Since 2015, NASA has been developing a 1–10-kW small reactor called "Kilopower" (Fig. 3) which uses sodium heat pipes to transport heat from the core to the Stirling engine conversion system, and a water heat pipe to release waste heat through the radiator. [5] The Kilowatt Reactor Using Stirling TechnologY (KRUSTY) (Fig. 3.) which was designed to demonstrate the performance of the Kilopower reactor power system, and the test results show that space fission technology can be developed affordably. [6]

The heat pipe in the solid core of space nuclear reactor is usually designed to be welded together with high thermal conductivity material. Assume the amount of fission heat removed by heat pipe and the length

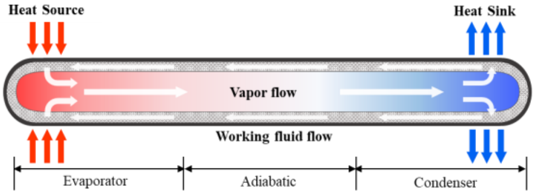

Fig. 1. Structure of heat pipe.

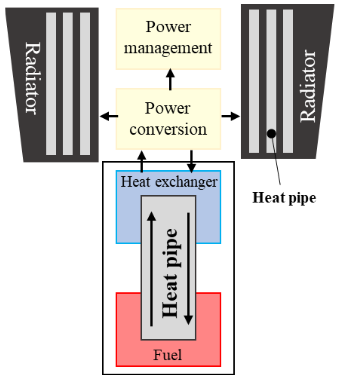

Fig. 2. Concept of heat pipe cooled reactor.

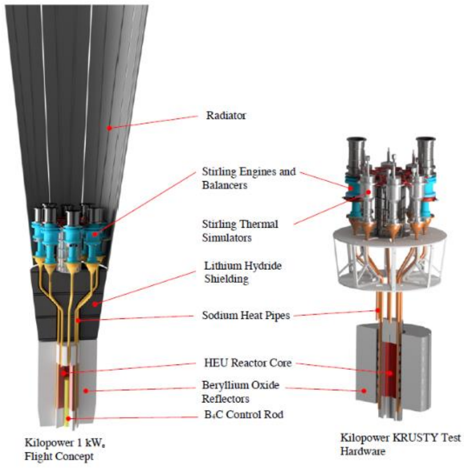

Fig. 3. Configuration of Kilopower (left) and KRUSTY (right). [6]

between the core and heat sink is determined, then the number of heat pipes inserted in core or reactor design such as total volume or weight will be decided according to the heat pipe diameter to remove a certain amount of heat. Therefore, it is important to optimize the design factors of the heat pipe to achieve for compact reactor designs given same power output.

In this study, among the various design parameters of the heat pipe, optimization of the heat pipe diameter was performed by investigate the heat pipe performance according to the length / diameter ratio. Moreover, the experiments will be performed to estimate the thermal performances and deduce the optimal diameter of the heat pipe for space nuclear reactor applications.

2. Heat pipe performance according to diameter

2.1 Operation limits

To evaluate the effects of diameter on heat pipe thermal performance, theoretical analysis was performed with existing correlations before the heat pipe experiments.

The operation limits determine the maximum heat transfer capacity of the heat pipe which is occurred due to the design limitations such as working fluid properties, wick structure, or operating conditions. If heat load from heat source excess the operation limits, heat pipe performance fails due to dry out in evaporator section. There are several operation limits such as capillary limit, boiling limit, entrainment limit, sonic limit, and viscous limit. The operation limits of the heat pipe according to the heat pipe diameter was investigated with existing correlations [7] for 1 m long heat pipe, 2 layers of 100-mesh screen wick, use water as a working fluid and in horizontal condition. Result in Fig. 4 (a) for 12.7 mm outer diameter show that the viscous limit is the dominant operation limit in lower operating temperature and in higher operating limit region capillary limit determines the maximum heat transfer capacity of the heat pipe. In case of O.D = 19.0 mm and 25.4 mm, capillary limit was shown to be the dominant operation limit in the overall temperature range.

2.2 Pressure drop in heat pipe

As the capillary limit was the most dominant operation limit in this case study, and the theoretical analysis with the correlations of pressure drop terms included in capillary limit was performed according to the diameter of the pipe.

There are several pressure differences occurred in heat pipe; gravitational pressure difference (ΔP_g) due to the hydrostatic head of liquid, capillary pressure (ΔP_{cap}) which is the driving force of the heat pipe occurred due to the pressure difference across the curved liquid surface in the wick, and the pressure difference caused by frictional forces in liquids and vapor flow in a heat pipe. ($\Delta P_v, \Delta P_l$) In order for the heat pipe to operate, Eq. (1) should be satisfied where the maximum capillary driving force must overcome the total sum of the pressure drop in right side. For space nuclear reactor, gravitational pressure can be neglected.

$$\Delta P_{cap} \geq \Delta P_v + \Delta P_l + \Delta P_g \qquad (1)$$

The capillary pressure is determined by the capillary radius of the heat pipe as described in Eq. (2). Because

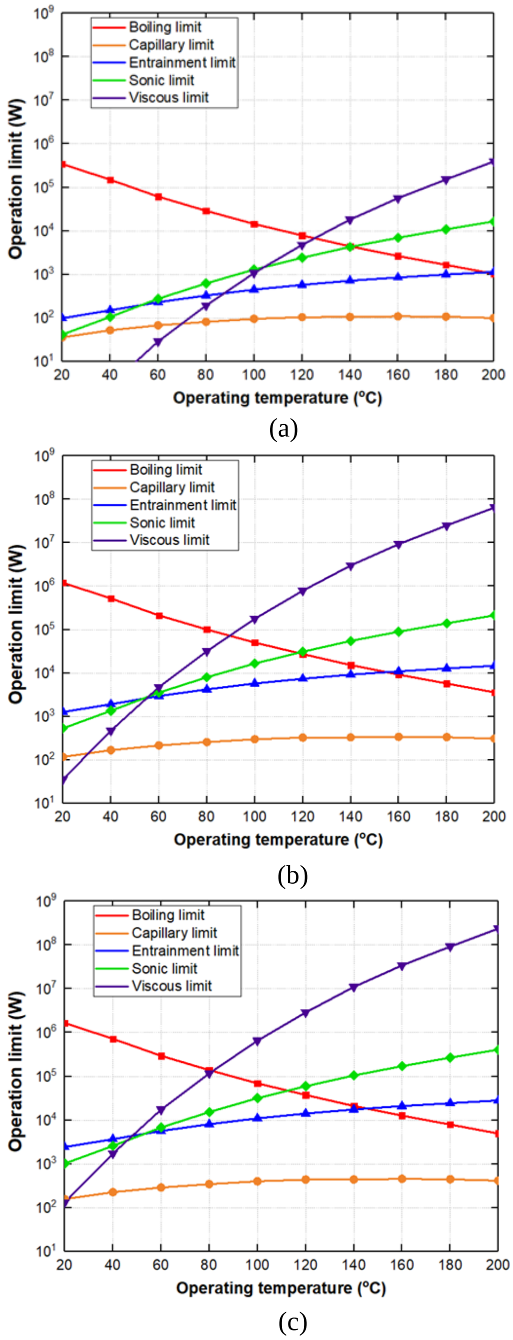

Fig. 4. Operation limits according to heat pipe outer diameters (a) O.D = 12.7mm, (b) O.D = 19.0 mm, (c) O.D = 25.4 mm.

the capillary driving force remain constant when apply same wick structure with same capillary radius, the frictional pressure difference of vapor and liquid terms should be analyzed to compare the difference in heat pipe performance with different diameter.

$$\Delta P_c = \frac{2\sigma}{r} \qquad (2)$$

The pressure drops caused by vapor and liquid is described in Eq. (3) and (4). The pressure difference due to friction forces is affected by the different pipe diameters. The maximum heat transport in a heat pipe can be obtained from the Eq. (5) where the $\dot{m}$ is the maximum liquid flow rate in the wick and λ is the latent heat of vaporization. The Eq. (3) and (4) can be converted using Eq. (5).

$$\Delta P_v = \frac{f_v \mathrm{Re}_v \mu_v}{2r_{hv}^2 A_v \rho_v \lambda} L_{eff} q \quad (3)$$

$$\Delta P_l = \frac{\mu_l}{K A_w \lambda \rho_l} L_{eff} q \quad (4)$$

$$Q = \dot{m}\lambda \quad (5)$$

From Eq. (1)~(5), the mass flow rate of the liquid can be described as Eq. (6).

$$\dot{m} = \frac{2\sigma}{r} \frac{1}{L_{eff}} \left(\frac{f_v \mathrm{Re}_v}{2r_{hv}^2 A_v^2 \rho_v} + \frac{\mu_l}{K A_w \rho_l} \right)^{-1} \quad (6)$$

Except for the parameters related to the working fluid and determined dimensions, the vapor flow area and wick cross section area affects to the mass flow rate. As the vapor flow area and wick cross section area increases with larger diameter, the mass flow rate of the liquid flow will also increase which leads to the enhancement of the heat transport through heat pipe.

The larger diameter of heat pipe will allow larger vapor flow cross section, and higher vapor volume to be transported from evaporator to condenser. Not only for the capillary limit, other operation limits also directly affected by the vapor cross section area. Analysis on other operation limits should be conducted for further work. Also, because the performance of the heat pipe decreases for reduced diameter with same length, to overcome the limitation of the small diameter, the thermal performance can be compensated by increasing the wick cross section area by adding additional wick such as artery or screen mesh.

3. Experimental setup

An experimental study will be performed and compared with theoretical analysis results to investigate the thermal performance of the heat pipe according to the outer diameter and wick types.

The heat pipe experimental facility which is shown in Fig. 5. consists of a test section, a water jacket at the condenser, a vacuum pump, a pressure gauge, a pump that circulates coolant through the water jacket, and two copper electrodes connected with the power supply to apply heat to the evaporator. To measure the wall temperature of the heat pipe test sections, K-type thermocouples were installed on each section.

The experimental conditions are described in Table. I. Several L/D ratio was selected as shown in Table. II. to compare the thermal performance difference and to investigate the performance enhancement when apply different types of wick to smaller diameter to overcome the limitation.

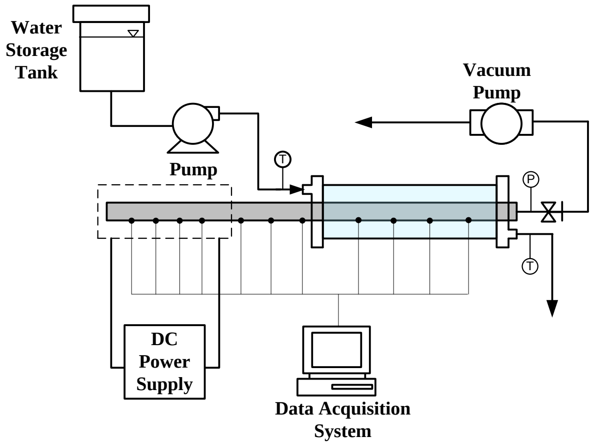

Fig. 5. Schematic diagram of heat pipe experimental facility.

Table I: Heat pipe experimental conditions.

Parameters	Value
Pipe material	SS304
Working fluid	Water
Fill ratio (%)	100
Length ratio (evp:adi:con)	1:2:1
Heat load (W)	30-1000
Pressure (bar)	0.2
Orientation	Horizontal

Table II: Experimental cases with various outer diameter.

Case	O.D [mm]	L/D ratio	Wick structure
A	25.4 (1 in)	31.5	200 mesh
B	19.0 (3/4 in)	42.1	200 mesh
C	12.7 (1/2 in)	63.0	200 mesh
D	25.4 (1 in)	31.5	100 mesh
E	19.0 (3/4 in)	42.1	100 mesh
F	12.7 (1/2 in)	63.0	100 mesh
G	19.0 (3/4 in)	42.1	100 mesh +200 mesh

The experimental procedure is as follows: (1) Set the pressure in the test section as 0.2 bar to remove the non-condensable gas using vacuum pump; (2) Fill the test section with working fluid; (3) Heat the evaporator gradually until the temperature of the adiabatic section reaches to saturation temperature in each step; (4) Flow the water through the water jacket located at the condenser section. The water flow in the water jacket should be adjusted to maintain the temperature of the condenser surface constant.

Based on the wall temperature distribution measurement results along the axial direction of the heat pipes, the thermal resistance and the heat transfer coefficient of evaporation and condensation will be investigated for further work.

4. Conclusions and Further works

There are limitations in weight and volume to use heat pipes as the passive heat transfer system from space nuclear core due to its maximum load capacity during the launch. To achieve optimum space nuclear reactor the analysis on diameter variation affecting the thermal performance of the heat pipe was performed with operation limit correlations. The results of the operation limit calculations according to the diameter showed lower maximum heat transfer capacity for smaller diameter. The mass flow rate of liquid flow in the heat pipe was also analyzed in terms of the pressure drops occurred in heat pipe. As the vapor flow area and the wick cross section area affect the mass flow rate of the liquid flow, it can be concluded that the larger diameter can transport higher heat from the heat source.

The heat pipe thermal performance evaluation experiment will be conducted according to the heat pipe diameter and to evaluate the diameter effects on heat pipe performance, thermal resistance and heat transfer coefficient will be investigated based on the experimental results for further works. Further research is necessary regarding to suggestion of thermal performance enhancement method for heat pipe with smaller diameter for optimum space nuclear reactor design.

ACKNOWLEDGEMENT

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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 of vaporization
ψ	tilt angle

Subscripts

adi	*adiabatic section*
c	*condenser*
cap	*capillary*
con	*condenser section*
e	*evaporator*
evp	*evaporator section*
g	*gravity*
in	*inch*
m	*mass flow rate*
r	*capillary radius of wick*
q	*heat transfer rate*

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