Performance evaluation of bending heat pipe for space nuclear reactor radiator application

[a]Ye Yeong Park, [a]In Cheol Bang *, [b]Chan Soo Kim
[a]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*
[b]Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, Korea

1. Introduction

Heat pipe is highly effective passive heat transfer device driven by capillary pumping force in porous media, which has been widely used in electronics and aerospace fields. Adopting heat pipe as heat transport system for nuclear reactor has advantages of providing passive heat transport without additional power or pump, simple structure and allowing free geometry design. Therefore, to ensure sufficient thermal safety margin not only during reactor accidents but also during normal operation, heat pipes are attracting attention as key component for innovative passive cooling nuclear reactors and are actively being used as passive heat transfer system for newly proposed reactor designs of MegaPower, Evinci, etc. With advantage of zero-gravity operation, various concepts of heat pipe cooled space nuclear reactor were also proposed. Heat pipe in space nuclear reactor transport heat from core to power conversion system and remove waste heat from power conversion through radiator heat pipe to space.

The maximum heat transfer capacity of a heat pipe is determined by various design parameters such as working fluid, geometry, wick structure, or material. Therefore, heat pipe cooling system of space nuclear reactor requires optimized heat pipe design depending on the operating environment. Based on the investigations of effects of design parameters to heat pipe performance, derive the optimal design of heat pipe with heat transfer performance that can sufficiently remove target waste heat from the power conversion system of the space nuclear reactor.

In this study, as part of the design optimization process of heat pipe for space nuclear reactor radiator application, evaluation of the operating limits and experiments will be conducted to understand how bending of heat pipe affects the thermal performance.

2. Heat pipe for space nuclear reactor application

2.1 Operating conditions of heat pipe radiator

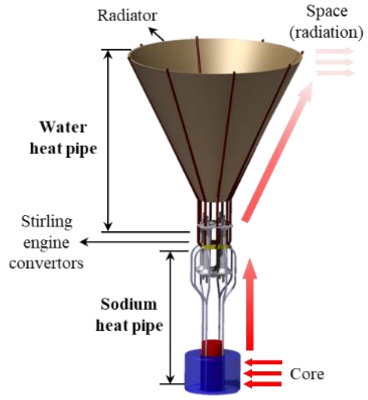

Fig. 1. Concept of heat pipe cooled space nuclear reactor (Kilopower, NASA) [1]

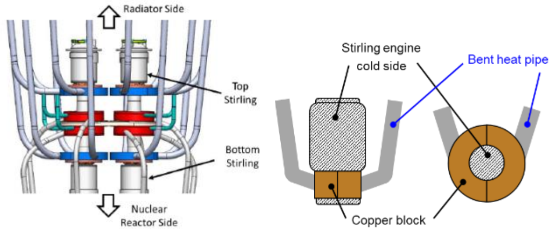

Fig. 2. Connection of heat pipe and cold side Stirling engine. [1]

Table. I: Operating conditions of heat pipe for space nuclear reactor.

Parameters	**Value**
Total waste heat removal [W]	4000
Heat pipe operating temperature	150 – 170
Radiator heat pipe length	1 – 1.5
Radiator heat pipe diameter [mm]	19.0
Radiator heat pipe material	Titanium
Operating environment	Zero-gravity

For removal of waste heat from Stirling engine, radiator heat pipe can be applied as passive heat transport system. Radiator heat pipe consist of evaporator section contact with cold side of Stirling engine, adiabatic section and condenser section where radiator panel is attached to transport heat via radiation heat transfer. Adiabatic section of radiator heat pipe should be bent in order to avoid structural contact between Stirling engine and radiator panel as shown in Fig. 2. In this research, the target total waste heat removal through heat pipes for space nuclear reactor is 4 kW. Detailed operating conditions of radiator heat pipe is described in Table. I. As bending of heat pipe can deteriorate the performance of heat pipe, which cannot provide sufficient waste heat removal from power conversion system, investigating the effect of bending and derive optimal design to overcome the bending effect is necessary.

2.2 Effects of bending on heat pipe performance

Bending heat pipe can cause distortion of wick structure which can affect the circulation of working fluid through capillary pumping force. Also, additional pressure drop of liquid and vapor flow will be induced in bending section. Due to the pressure drop occurred by bending, the transport resistance of vapor will increase and eventually decrease the thermal performance of the heat pipe. To investigate the effect of bending, operation limit of heat pipe was calculated theoretically. The operation limit such as capillary limit, sonic limit, entrainment limit, viscous limit and boiling limit determines the maximum heat transport capacity of the heat pipe which is affected by various design parameters and operating conditions. Among the various operation limits, capillary limit usually limits the low-temperature heat pipe operation which encountered when the capillary pumping pressure in porous media is not sufficient to pump the liquid from condenser to evaporator section and cause the dry out of the wick at evaporator section.

Among the various operation limit, when the heat pipe has single bend section, the only limit affected is capillary limit due to change in flow paths of vapor and liquid. Therefore, only the capillary limit was examined according to various bending conditions.

The thermal performance of radiator heat pipe in this study requires about 500W of waste heat removal capability per single unit in operating temperature between 140 to 180°C.

3. Performance evaluation of bent heat pipe radiator

To investigate the effects of bending on heat pipe performance, theoretical evaluation of heat pipe operation limit was preliminarily performed, and experimental evaluation will be performed for further work.

3.1 Bent heat pipe operation limit

In bent heat pipe, the vapor pressure drop and liquid pressure drop due to bending will be affected due to distorted flow paths. The configuration of adiabatic section of bent heat pipe is shown in Fig. 3. D.D.Odhekar (2005) proposed capillary limit correlation by considering pressure drop induced due to bending in terms of bend loss coefficient using Dean number (Equation 1) which is relative radius of the curvature, and friction factor to compare the effect of bending radius and bending angle to heat pipe performance as written in Equation. 2.

The relationship between Dean number and bend loss coefficient was compared for operating temperature 140°C as shown in Fig. 4. In case of large bending angle, the bend loss coefficient increases until the Dean number reaches to 60 and decrease again as the Dean number increase. Similar aspects were observed in the change in bend loss coefficient, but for smaller bending angle, the effect of Dean number to bend loss was smaller compared to larger bending angle. Therefore, the capillary limit of heat pipe will be influenced by change in bending angle compared to bending radius.

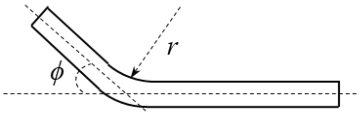

Fig. 3. Bent heat pipe configuration.

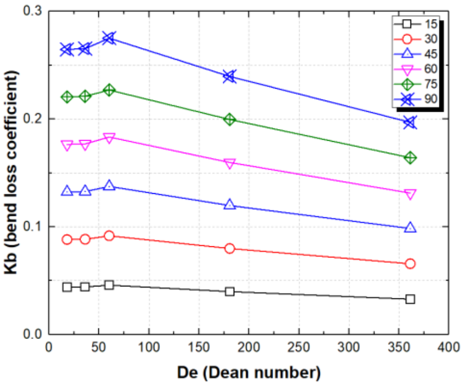

Fig. 4. Relation between *De* and K_b

Using bend loss coefficient in Equation 2, pressure drop due to bending heat pipe can be described as Equation. 3. The capillary limit induced when capillary pumping force cannot overcome the sum of pressure drop occurred in heat pipe such as liquid pressure drop, vapor pressure drop and gravitational pressure drop. (Eq. 4) From Eq. 1 ~4, correlation of capillary limit for bending heat pipe can be described as Eq. 5.

$$De = \mathrm{Re}\sqrt{\frac{R_v}{r}} \tag{1}$$

$$K_b = \frac{f_s r\phi}{2R_v}\left(0.1033De^{0.5}\left[\left(1+\frac{1.729}{De}\right)^{0.5} - \frac{1.315}{\sqrt{De}}\right]^{-3} - 1\right) \quad (2)\ [3]$$

$$\Delta p_{bend} = K_b\frac{\rho w^2}{2} = K_b\frac{{Q_e}^2}{2\rho {A_v}^2{h_{fg}}^2} \tag{3}$$

$$\Delta P_{capillary} \geq \Delta P_{liquid} + \Delta P_{vapor} + \Delta P_{gravitational} + \Delta P_{bend} \tag{4}$$

$$Q_c = \frac{\dfrac{2\sigma}{r_{ce}} - \rho_l g d_v \cos\psi - K_b\dfrac{{Q_e}^2}{2\rho {A_v}^2{h_{fg}}^2}}{\left(\dfrac{f_v \mathrm{Re}_v \mu_v}{2r_{hv}^2 A_v \rho_v \lambda} + \dfrac{\mu_l}{KA_w \lambda \rho_l}\right)L_{eff}} \tag{5}$$

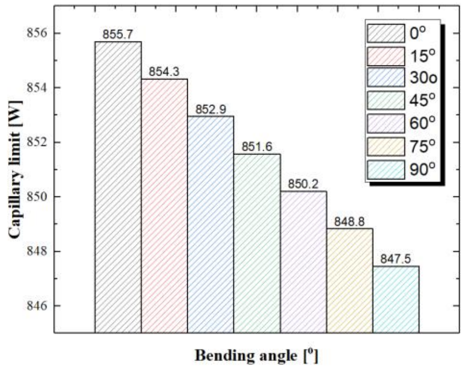

Fig. 5. Capillary limit result for various bending angle

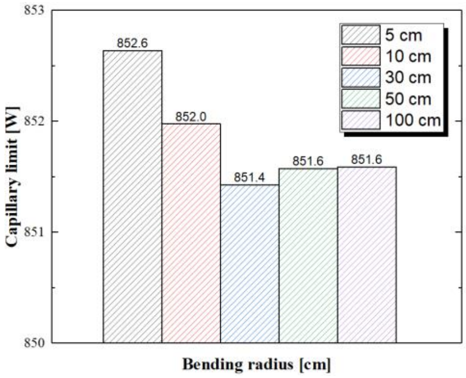

Fig. 6. Capillary limit results for various bending radius.

Table. II: Ratio of pressure drop

Type of pressure drop	Result [Pa]	Ratio [%]
$P_{capillary}$	177.74	55.5
$P_{gravitational}$	121.99	38.1
$P_{bending}$	0.31	0.1
P_{liquid}	17.55	5.5
P_{vapor}	2.69	0.8

When the input power of the exceeds the operating limit, the operation of the heat pipe is limited by the steam-liquid circulation disturbance inside the pipe, so a capillary limit of heat pipe according to bending radius and bending angle was calculated as shown in Fig. 5 and 6. In Fig. 5, the bending radius was fixed as 0.3 m, and for Fig. 5, the bending angle was fixed with 45^{o}.

The capillary limit of radiator heat pipe with outer diameter of 19.0 mm, groove wick, 1 m length was calculated at operating temperature 140^{o}C as shown in Fig. 5 and 6. As bending angle increases capillary limit decreases for overall operating temperature. Also, for smaller bending radius, capillary limit decreases. However, compared to effect of bending angle, variation of bending radius effect was negligible. For overall bending variation, the amount of heat transfer meets the target waste heat removal.

The decrease of capillary limit due to bending structure of the heat pipe was very small. Therefore, the ratio of pressure drops occurred due to various reasons inside heat pipe such as capillary, gravity, vapor flow, liquid flow and bending was evaluated to observe the amount of effect of bending of the heat pipe compared total pressure drop induced inside the heat pipe when bending radius is 0.3 m and bending angle is 30^{o} and operating temperature at 140^{o}C is described in Table II. The pressure drops due to bending showed lowest ratio about 0.1 % compared to total pressure drop occurred in heat pipe. The change in bend loss coefficient according are clear as shown in Fig. 4, but when it reflected to capillary limit correlation, it did not seriously affect to the capillary limit decrease.

3.2 Bent heat pipe experimental setup

Based on the capillary limit evaluation, bending of heat pipe did not seriously deteriorate the performance of the heat pipe. However, affect of wick deformation due the bending process was not reflected in capillary limit correlation. Therefore, the real heat pipe performance variation due to bending process should be evaluated through experiment and compared with operation limit calculation result.

An experimental study will be performed to investigate the thermal performance of heat pipe according to the bending radius and angle. The heat pipe test facility consists of cartridge heater, cooling jacket, and test section as shown in Fig. 6. K-type thermocouples will be used in outer wall of heat pipe test section to measure the wall temperature distributions of heat pipe. The detail dimensions of test sections and experimental conditions are shown in Table. II. Experiment will be performed as follows: Apply power to evaporator until the working fluid is sufficiently heated, then cooling condenser with compressed air. After steady-state of wall temperature was achieved for each step, apply additional heat input for further steps. The wick structure of bent heat pipe will be fabricated with metal 3D printing which has advantages for easier fabrication and prevent distortion of wick at bending section.

4. Summary and Further plan

Heat pipe radiator is adopted for passive heat transport system to remove waste heat from power conversion system of space nuclear reactor. As heat pipe should be designed to be bent at adiabatic section in order to meet the required configuration of the space nuclear reactor, investigation of bending effect on heat pipe performance was performed in aspect of heat pipe operation limit. The theoretical calculation results showed that the maximum heat transfer capacity of bent heat pipe decreases with decreasing bending radius and

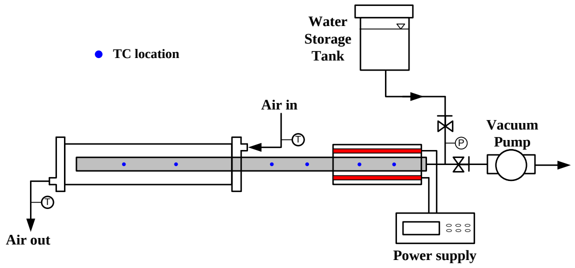

Fig. 6. Schematic diagram of heat pipe experimental setup.

Table. II: Heat pipe experimental conditions.

Parameters	**Value**
Heat pipe material	SS316L
Heat pipe length [m]	1.0 – 1.5
Heat pipe diameter [mm]	19.0
Working fluid	Water
Fill ratio [%]	100
Heat load [W]	50-400
Orientation	Horizontal

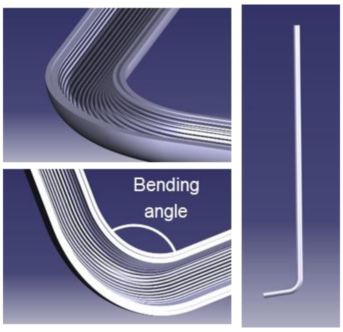

Fig.7. Bent heat pipe geometry with 3D-printing.

increasing bending angle. Heat pipe experiment will be performed to evaluate the effects of bending to heat pipe thermal performance with various bending radius and bending angle.

NOMENCLATURE

A	area [m^2]
g	gravity [m/s^2]
K	permeability of the wick [m^2]
P	pressure [kPa]
Q	heat input, power [W]
Re_v	Reynolds number of vapor

Greek-letters

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

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