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Design of heat pipe radiator for thermal management system in space nuclear reactor

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1. Introduction

A heat pipe is a passive, high thermal conductance heat transfer device driven by capillary pumping force. With advantages of zero gravity operation, simple design and light weight, the nuclear reactor concept cooled by heat pipe has been proposed for space propulsion. Heat pipe cooled space nuclear reactor transfer heat from core to Stirling engine with several alkali metal heat pipe inserted in core and release the residual heat from Stirling engine to surroundings through heat pipe radiator. To achieve higher reactor power output and compact reactor design, the performance of the heat pipe heat transfer system should be designed to be maximum. Radiator heat pipes are located on the cold side of the Stirling engine to remove the residual heat into the space. Optimum design parameters for radiator heat pipe should be selected to prevent the overheating or overcooling of the reactor system and accommodate the range of temperature variation of the space. The performance of the radiator heat pipe is determined by various design factors such as material, heat transfer area, or geometry.

In the present study, the parametric study of the heat pipe radiator was conducted to enhance the thermal performance of the heat pipe and achieve a compact design for space nuclear reactor application.

2. Heat pipe radiator for space nuclear reactor thermal management

2.1 Heat pipe cooled space nuclear reactor

The operating conditions and required power of the heat pipe radiator are described in Table. I. The target power output of the proposed nuclear reactor is 1kWe (5kWth) for space propulsion. The 4kW waste heat of the Stirling engine is removed into space through 12 radiator heat pipes. The required heat removal rate for a single radiator heat pipe is about 340W. To transfer heat from the Stirling engine, the evaporator section of the heat pipe is connected to the cold side of the Stirling engine with a heating block consisting of high thermal conductivity material. On the surface of the moon or Mars, the surrounding temperature changes on time, and the temperature range of the Stirling engine that determines the temperature of the evaporator outer surface varies, so the radiator heat pipe should be designed to remove heat sufficiently within this temperature variation.

Table I: Design requirements of the heat pipe radiator

Operating parameters	Value
Total residual heat removal rate	4 kW
Total number of radiator heat pipe	12
Target heat removal rate of single radiator heat pipe	340 W
Heat sink(space) temperature	-130 ~ 100 °C
Stirling engine cold side temperature	120 ~ 180 °C

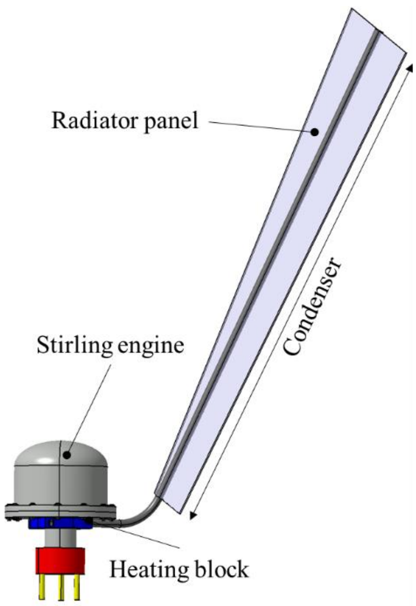

Fig. 1. Configuration of Stirling engine and heat pipe radiator assembly.

2.2 Design requirements and considerations of radiator heat pipe

The radiator heat pipe consists of a heating block that transports waste heat from the Stirling engine to the evaporator section and condenser section where the radiator panel is attached to release heat to space with radiation as shown in Fig. 1. When the waste heat is applied to the evaporator, the vapor is generated by the phase change of working fluid and transported to the condenser section and released heat to the radiator panel then condensed working fluid returns to the evaporator section through a wick structure driven by capillary pumping force. The heat pipe radiator was bent to accommodate the size of a compact reactor.

Among the design parameters, heat removal rate and total mass of radiator showed contradictory characteristics. The heat removal capacity of the heat pipe radiator increases in proportional to the increase in the area of the radiator panel, but at the same time, the total weight of the radiator also increases, which is unbeneficial to the launch of a space nuclear reactor. Therefore, it is necessary to select a heat pipe radiator design factor capable of satisfying the total weight of the reactor while having sufficient heat removal capacity.

Specific parameter values of heat pipe radiator are described in Table. II. Water with high latent heat was used as a working fluid, and titanium was selected as a material for heat pipe containers in consideration of long-term compatibility with water. For the capillary wick structure of the heat pipe, groove wick was used which is advantageous for long-distance heat transport and high permeability. In addition, lightweight and high emissivity aluminum was selected as a panel material.

3. Performance evaluation of heat pipe radiator

3.1 Operation limit of heat pipe radiator

The operation limit is the maximum heat transfer capacity of the heat pipe which is limited by various design factors and conditions. Types of operation limits of the heat pipe are capillary, viscous, sonic, entrainment, and boiling limit. Among the operation limit, capillary, entrainment and viscous limit can restrict the function of the heat pipe. The thermal capacity of the heat pipe radiator should be designed with a 1/2 or 1/3 margin to the operation limit of the heat pipe to ensure the stability of the reactor. [1] Therefore, the evaluation of the operation limit of heat pipe was conducted and compared with the heat transport capacity of heat pipe radiator to design a radiator heat pipe having a thermal margin and the capacity to remove sufficient waste heat.

The equations used for capillary, boiling, and viscous limit calculation are shown in Eq. (1) ~ (3). Capillary, viscous and boiling limits are affected by changes in the length of the evaporator section, and viscous, boiling limits are influenced by the condenser section length. The calculation results of operation limit according to evaporator and condenser length are shown in Fig. 2 and 3.

$$q_{capillary} = \frac{\dfrac{2\sigma}{r_{ce}}}{\left(\dfrac{f_v \mathrm{Re}_v \mu_v}{2 r_{hv}^2 A_v \rho_v \lambda} + \dfrac{\mu_l}{K A_w \lambda \rho_l}\right) L_{eff}} \quad (1)[5]$$

$$q_{boiling} = \left(\frac{2\pi L_e k_{eff} T_v}{\lambda \rho_v \ln(r_i / r_v)}\right)\left(\frac{2\sigma}{r_n} - \frac{2\sigma}{r_{eff}}\right) \quad (2)[5]$$

$$q_{viscous} = \left(\frac{A_v r_v^2 \lambda \rho_v P_v}{16 \mu_v L_{eff}}\right) \quad (3)[5]$$

Table II: Specifications of radiator heat pipe

Parameters	Value
Heat pipe outer diameter	19.0 mm
Total heat pipe length	1~3 m
Heat pipe material	Titanium
Working fluid	Water
Wick type	Groove
Radiator panel material	Aluminum
Emissivity of radiator panel	0.8

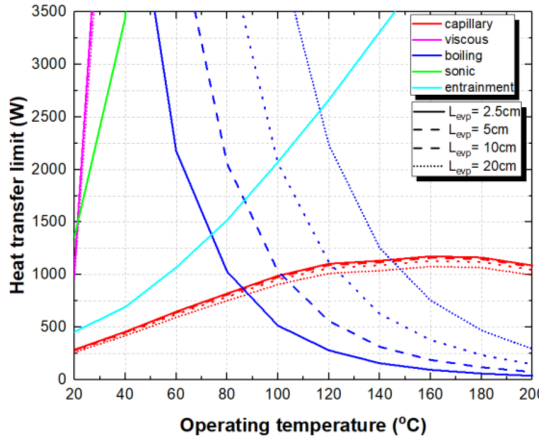

Fig. 2. Operation limits according to evaporator length variation

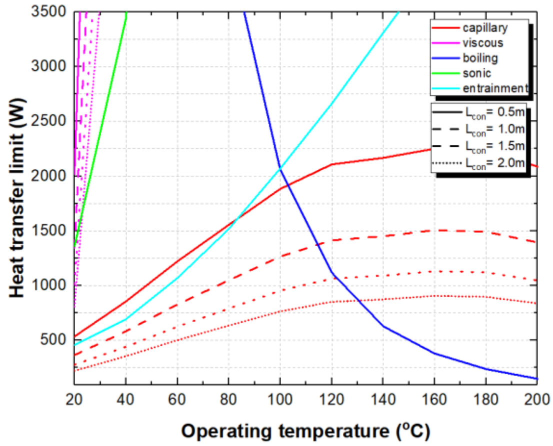

Fig. 3. Operation limits according to condenser length variation

As shown in Fig. 2, The capillary, viscous, boiling limits are increasing according to the increasing evaporator length. Especially boiling limit is highly affected by the evaporator length variation. Due to the short length of the heat transfer area through the Stirling engine to the evaporator section, heat pipe operation is limited by boiling limit in the range of operating temperature between 120°C~160°C.

As the length of the evaporator increases, the heat flux decreases, and thus wetting at the interface between the working fluid and wick increases, reducing the contact angle which leads to the increase of capillary pressure and heat transport rate. On the other hand, as the length of the evaporator section decreases, the heat flux increases, and a large amount of vapor is generated. This results in the increase in the pressure difference between the evaporator and condenser section resulting in limiting the circulation of working fluid by capillary force.

According to the increase in condenser length, capillary and viscous limits are also increased as shown in Fig. 3. As the length of the condenser increases, vapor transported from the evaporator condensed earlier and results in a large amount of condensed working fluid generated which can limit the circulation of the working fluid. However, along with the condenser length increases, the amount of heat released through the radiator panel also increases. Therefore, selecting the optimum design point is required.

3.2 Heat transfer performance of heat pipe radiator

To evaluate the heat pipe radiator performance for various range of design parameters, a thermal resistance network model was used for calculation. The thermal resistance network of heat consists of conduction resistance occurred in the heat pipe container, wick structure, and radiator panel, convection resistance for phase change of working fluid and radiative resistance occurring between radiator surface and space. Several assumptions were made for the calculation. 1) assume that the vapor resistance is negligible and axial thermal resistance can be assumed as an open circuit. 2) Uniform heat flux distributed along with the condenser and evaporator of the heat pipe. 3) Consider radiative heat transfer occurs on both sides of the radiator. The radiative heat transfer rate was calculated using the Stefan-Boltzmann law described in Eq. (4).

$$Q = \varepsilon \sigma A T^4 \qquad (4)$$

The results of the comparison between the operation limit and heat transfer capacity of heat pipe radiator in the range of operating temperature for various evaporator/condenser lengths are shown in Fig. 4 and 5.

In Fig. 4, the heat transfer rate increases with increasing evaporator length. Although the heat transport rate was designed to remove all of the target residual heat, if the required heat removal rate exceeds the boiling limit, the heat pipe operation will fail due to high heat flux in the evaporator section which could lead to the dry out of the evaporator section. Therefore, the length of the evaporator should be designed to be at least 10 cm as the radiator heat pipe is required to remove waste heat of 340W. Fig. 5. shows the results of operation limit and heat transport rate comparison according to the condenser length variation. The amount of heat radiated from the radiator panel is fourth proportional to the fourth of surface temperature and heat transfer area. As the condenser length increase, the radiator panel area also increases.

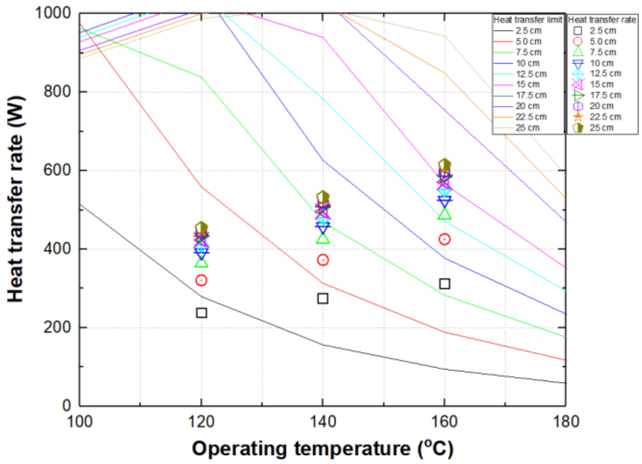

Fig. 4. Comparison between heat removal rate and operation limit of heat pipe radiator according to the evaporator length

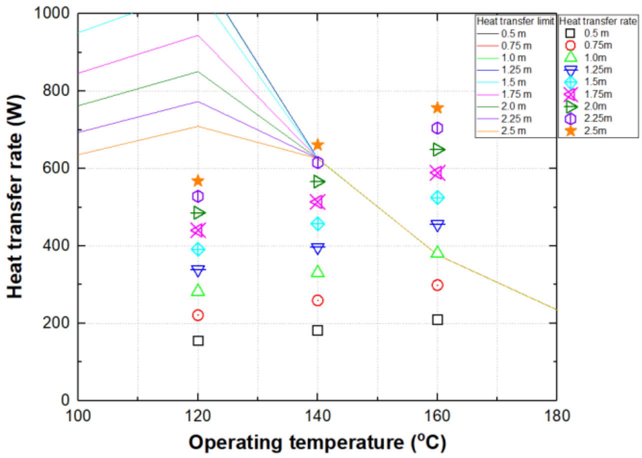

Fig. 5. Comparison between heat removal rate and operation limit of heat pipe radiator according to the condenser length

The operation limit and heat transfer rate of the heat pipe showed opposite trends according to the length variation. To satisfy the required heat removal rate and has a thermal margin to the operation limit at the same time, the length of the condenser should be designed between 1.0 ~ 2.0 m.

4. Conclusions

In the present study, the performance of the heat pipe radiator was evaluated in terms of operation limit and heat transfer rate in a certain operating temperature range according to the variation of the evaporator and condenser length. According to the results comparing the operation limit and heat transport rate according to the changes in evaporator/condenser length, for the heat pipe with a diameter of 19mm, the evaporator section of heat pipe should be designed to be longer than 10cm, and for condenser length, it should be design between 1.0 ~ 2.0 m range to satisfy the design requirement. Performance evaluation using SINDA/FLUINT software will be conducted for further work for verification of the analysis results. Additionally, the consideration of the view factor will be also conducted as a further work after the structural arrangement of the radiator heat pipes has been determined.

ACKNOWLEDGEMENT

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NOMENCLATURE

A	area [m^2]
C	correlation coefficient
F	friction factor
g	gravity [m/s^2]
h	heat transfer coefficient [W/m^2 K]
K	permeability of the wick [m^2]
L	length [m]
P	pressure [kPa]
Q	heat input, power [W]
R	thermal resistance [^{o}C/W]
Re_v	Reynolds number of vapor
r	radius [m]
T	temperature [^{o}C]

Greek-letters

σ	surface tension
μ	Viscosity
ρ	Density
λ	latent heat off vaporization
ψ	tilt angle

Subscripts

c	condenser
e	evaporator
eff	effective
i	inner
o	outer
q	heat transfer rate