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Design Study of Heat Pipes for Nuclear Spaceship Applications

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

1. Introduction

A heat pipe is a heat transfer device driven by a phase change of working fluid. The circulating flow of the working fluid in the heat pipe is dominated by a capillary phenomenon from the wick structure. After working fluid heated at the evaporator section, vapor flows to the condenser section as shown in Fig. 1. The condensed working fluid moved from the condenser part to the evaporator part by capillary phenomenon where the wick acts as a pump for moving the working fluid.

To prevent core damage in nuclear power plant, passive decay heat removal system using heat pipe have been developed. Jeong et al. [1] suggested an innovative hybrid control rod concept which combined the function of neutron absorption with the original function of the heat pipe. The heat pipe can be also applied to spent nuclear fuel storage for passive cooling. Xiong et al. [2] proposed a loop-type heat pipe as a two-phase thermosyphon and Jeong and Bang [3] suggested passive decay heat removal device for the dry storage cask of spent nuclear fuel with a hybrid heat pipe system named UCAN (UNIST CANister) to achieve enhanced cooling performance and waste heat generation.

Since the fluid flows by the capillary phenomenon in the heat pipe, it was initially developed to use in zero gravity environment, space. The heat pipe is applied to satellite and spacecraft which has advantages in passive heat removal, highly efficient heat transfer in the space environment, structural simplicity and free shape design. The need for long-term and high-power sourced for space exploration, nuclear power was the most suitable source of electricity. It is being developed as a power system to use passive heat transfer without the additional pump, to have a simple structure, and achieve high reliability.

In this paper, the design study on the heat pipe for nuclear spaceship application is conducted in terms of the design factors. Various design factors of heat pipe such as types of working fluid, geometry, or wick structure are analyzed for application of heat pipe by calculating heat transfer limit and heat transfer capacity based on the thermal resistance model.

2. Design factors for spaceship applications

In 1967 Deverall and Salrni [4] conducted an experiment to check whether a heat pipe was driven in a zero-gravity environment, after first proposing a heat pipe with wick structure. The experiment was carried out by placing a heat pipe with a wick structure of 12 inches in length and 0.75 inches in diameter on the earth's orbit.

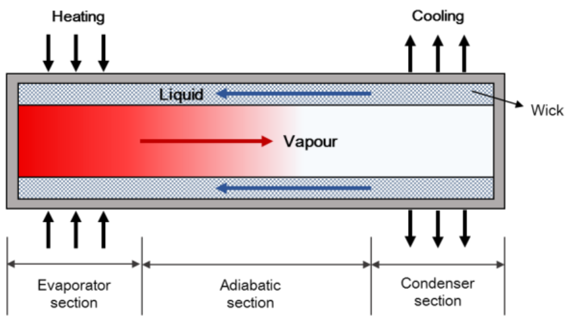

Fig. 1. Structure of heat pipe.

Even in a zero-gravity environment, it was shown to be applicable to spaceships when compared with the ground performance and thus it is applicable to spacecraft and satellite.

Riehl et al. [5] suggested Loop Heat Pipe (LHP) using the working fluid as acetone which was designed to accomplish the thermal management of up to 70W. LHP has advantages that working fluid operates at its pure state and very little power consumption is required. Also, they selected acetone as working fluid due to its tendency to substitute hazardous working fluids in two-phase capillary pumping.

NASA is developing Kilopower reactors since 2015 which is 1~10kW small reactor for supplying power to spacecraft, or space equipment which is shown in Fig. 2. [6]. Kilopower uses Stirling engine and cooled by a sodium heat pipe. Fig. 4. shows the concept of the Kilopower with sodium heat pipe. Los Alamos National Lab also developed small heat pipe reactor HOMER (Heatpipe-Operated Mars Exploration Reactor), with 15kW power, which performs cooling with 19 stainless steel sodium heat pipes.

Fig. 2. Concept of Kilopower with sodium heat pipe [6]

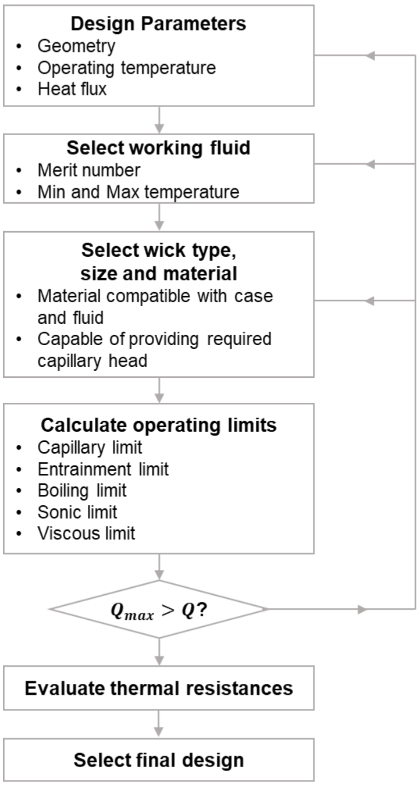

Fig. 3. The design procedure for a heat pipe [7].

There are several important factors to consider when designing heat pipe in accordance with the circumstances of the application. The design procedure for a heat pipe is outlined in Fig. 3. In case of the application in the spaceship, which is an extreme environment, there are several conditions to be considered such as zero gravity, or operating temperature range between 900K-1400K.

When selecting suitable working fluid for the heat pipe, operating vapor temperature range and variety characteristics should be considered such as compatibility with wick and wall materials, the wettability of wick, good thermal stability, high thermal conductivity, acceptable freezing point etc. [7]. Space reactors generally operate at 900K – 1400 K could be cooled with liquid-metal heat pipes with using either sodium (900 K–1100 K), lithium (1100 K–1400 K) or potassium (600 K-800 K) as working fluids. [8]

The primary purpose of the wick is to transport the working fluid from the condenser to the evaporator with capillary pressure. Capillary pressure is a function of wetting angle, surface tension and effective capillary radius of the wick structure as represented in equation [7].

Capillary pressure which is shown in equation (1) can be described with capillary heat at the evaporator and condenser. r is the effective radius of the wick pores and θ is contact angle. In addition, the heat transport capability of the heat pipe can be enhanced by increasing the wick thickness. However, the increased radial thermal resistance of the wick created by this would lower the allowable

(a) (b)

Fig. 4. The inner structure of heat pipe according to wick structure; (a) Hybrid screen-groove, (b) Self-venting arterial [9].

maximum evaporator heat flux.

$$\Delta P_c = \Delta P_e' - \Delta P_c' = 2\sigma_1 \frac{\cos\theta_e}{r_e} - 2\sigma_1 \frac{\cos\theta_c}{r_c} \qquad (1)$$

Heat transfer performances should be conducted depending on various types of wicks such as sintered artery wick, self-venting artery wick, grooved wick and hybrid grooved wick for application of space reactor heat pipe. By performing an experiment by changing the diameter, length or shapes of wick structure condition, optimal design factor for heat pipe can be determined. Fig. 7. shows the inner structure of the hybrid screen groove wick and self-venting arterial wick.

Examining the heat transfer limits of the heat pipe like capillary limit, entrainment limit, boiling limit, sonic limit, and viscous limit, the maximum heat transfer capacity of the heat pipe can be determined.

Capillary limit means that the net capillary pumping pressure between evaporator and condenser must be bigger than pressure losses which can be described as below equation (2) [10]:

$$(\Delta P_c)_m \ge \int_{L_{eff}} \left(\frac{\delta P_v}{\delta x} + \frac{\delta P_l}{\delta x}\right)dx + \Delta P_{ph,c} + \Delta P_{ph,e} + \Delta P_{+} + \Delta P_{ll} \qquad (2)$$

Then, the maximum heat transport capacity governed by the capillary limit can be described as equation (3).

$$Q = \frac{\frac{2\sigma}{r_{ce}} - \rho_l g (d_v \cos\psi + L_{eff} \sin\psi)}{\left(\frac{C f_v \mathrm{Re}_v \mu_v}{2 r_{hv}^2 A_v \rho_v \lambda} + \frac{\mu_l}{K A_w \lambda \rho_l}\right) L_{eff}} \qquad (3)$$

Where $(\Delta P_c)_m$ is the maximum capillary pressure difference generated within capillary wicking structure, $\frac{\delta P_v}{\delta x}$ and $\frac{\delta P_l}{\delta x}$ is the sum of inertial and viscous pressure drops occurring in the vapor phase and liquid phase, $\Delta P_{ph,c}$ and $\Delta P_{ph,e}$ is pressure gradient across phase transition in condenser and evaporator, ΔP_{+} and ΔP_{ll} is normal and axial hydrostatic pressure drop.

The maximum heat transport due to the entrainment limit may be determined from equation (4) below.

$$Q = A_v \lambda \left(\frac{\sigma \rho_v}{2 r_{hw}}\right)^{1/2} \qquad (4)$$

The boiling limit is caused by the bubble formation in the wick structure in the evaporator section as shown in equation (5) [10]:

$$Q=\left(\frac{2\pi L_e k_{eff} T_v}{\lambda\rho_v \ln(r_i/r_v)}\right)\left(\frac{2\sigma}{r_n}-\Delta P_{c,m}\right) \tag{5}$$

The minimum axial heat flux due to the sonic limitation will occur at the minimum operating temperature and can be calculated from the equation (6) [7]:

$$Q=A_v\rho_v\lambda\sqrt{\frac{\gamma_v R_v T_v}{2(\gamma_v+1)}} \tag{6}$$

Where z is the characteristic dimension of the liquid-vapor interface.

The viscous limit can be expressed as equation (7) which depends on viscous pressure losses in the vapor phase and the vapor pressure of the working fluid.

$$Q=\frac{A_v r_v^2 \lambda\rho_v P_v}{16\mu_v L_{eff}} \tag{7}$$

According to the given condition in Table. I., the total heat transfer rate can be calculated with equation (8).

$$Q=\frac{T_{hot}-T_{cold}}{R} \tag{8}$$

Table I: Design and conditions for heat pipe analysis.

Parameter	**Value**
Working fluid	Sodium
OD/wall thickness	15mm / 0.4mm
Orientation	2º (zero gravity)
Wick porosity (sintered)	0.52 (copper powder sintered, Pore radius = 9 e-6 m, K = 1.74 e-10 m^2)
Evaporator/Adiabatic/Condenser	0.42m / 1.84m / 1.23m (total 3.49m)
Te wall / Tc wall	929℃ / 915.5℃

In addition, various heat transfer limits mentioned above can be calculated with equations (3)-(7). Results of five different heat transfer limits are shown in Fig. 7. according to operating temperature. Fig. 7. showed that viscous limit is dominated at the lower temperature, the sonic limit between 700℃-900℃, and boiling limit at the higher temperature.

The result of heat transfer limits for each temperature range was compared with the total heat transfer rate calculated by equation (8) as shown in Fig. 8. Since heat transfer rate should not exceed the heat transfer limit, operation temperature will be 800℃ or higher. Also, as

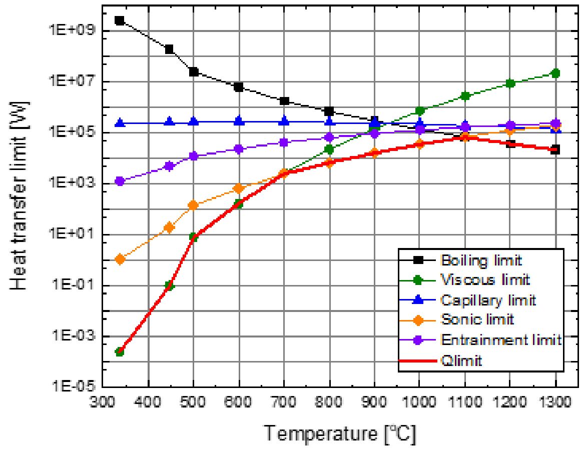

Fig. 7. Results of various heat transfer limits according to operating temperature.

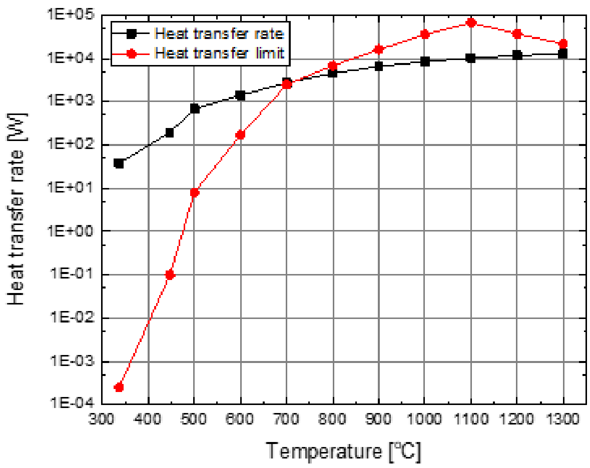

Fig. 8. Comparison between heat transfer limits and heat transfer rate according to operation temperature.

the operating temperature must be lower than the evaporation temperature, above 929℃ is not appropriate for operating temperature. So, it could be said that the operation temperature for sodium heat pipe should be between 800℃ to 900 ℃ which satisfied with the given conditions and heat transfer limits.

3. Summary & Future work

The heat pipe is used in many engineering fields, especially in the field of space nuclear reactors to remove the high heat capacity in absence of gravity and pumping power. In order to improve its efficiency, the optimal design factor of heat pipe should be considered. In this study, the process of considering design factors for application of heat pipe to spaceship was investigated based on the previous studies. In addition, the estimation of operating temperature by comparing various heat transfer limits and heat transfer rate under a given condition was performed for the sodium heat pipe.

Heat transfer rates and heat transfer limits were predicted for arbitrary sodium heat pipe design. As a result, under selected boundary conditions, the operating temperature range of sodium heat pipe, 800℃-929℃ was derived.

Heat pipes are affected by several design factors such as working fluid, operating temperature, wick structure and geometry. Therefore, we plan to carry out research to derive optimal heat pipe design for spaceship nuclear reactor applications. Research of optimal heat pipe design are expected to be considered as important factor for enhancement of the power generation and cooling efficiency of spaceship reactors.

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NOMENCLATURE

A	area
C	correlation coefficient
f_v	correlation coefficient for friction
P	pressure
R	gas constant
T	temperature
K	permeability of the wick
k_{eff}	effective thermal conductivity
L_{eff}	effective length of the pipe

Greek-letters

σ	surface tension
r	hydraulic radius
μ	viscosity
ρ	density
λ	latent heat of vaporization
ψ	tilt angle

Subscripts

c	condenser
e	evaporator
g	gravity
q	heat transfer rate

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