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Performance Analysis of Heat Pipe Design for Space Nuclear Reactor Application

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1. Introduction

A heat pipe is a passive thermal control device which has been applied for various engineering fields because of high heat transfer capability, zero gravity operation, structural simplicity.[1] The main driving force of the heat pipe is capillary pumping force and consists of evaporator, adiabatic and condenser sections, where the working fluid inside the heat pipe evaporates as the heat input at the evaporator 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 through the wick structure, as shown in Fig. 1.

To improve the stability of the nuclear reactor and achieve a simplified design, various concepts of space nuclear reactors using heat pipes as a cooling system have been developed. The systems of heat pipe cooled space reactor include 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 as shown in Fig. 2.[2] The advantages of using heat pipes in space nuclear reactors are zero gravity operation, passive and continuous heat removal from the reactor core after shutdown, high power output, self-containment, and lightweight. To transport heat from the core, liquid metal such as sodium, lithium, or potassium is used as a working fluid for high operating temperature. For radiator heat pipe, water is usually used as a working fluid.

To achieve maximum output for space nuclear reactor with heat pipe, the heat pipe design optimization is necessary by adjusting various design parameters or surrounding conditions. In this study, design optimization with heat pipe diameter will be conducted by comparing the experimental results with theoretical estimation to derive optimum heat pipe diameter for constant heat pipe length.

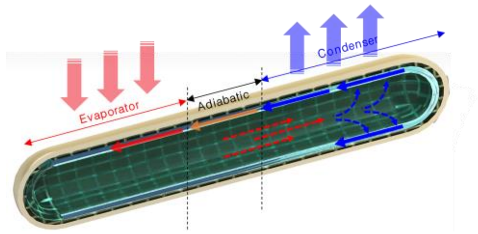

Fig. 1. Structure and working principle of heat pipe.

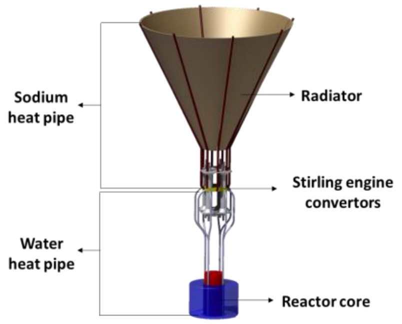

Fig. 2. Concept of heat pipe cooled space reactor. (Kilopower)

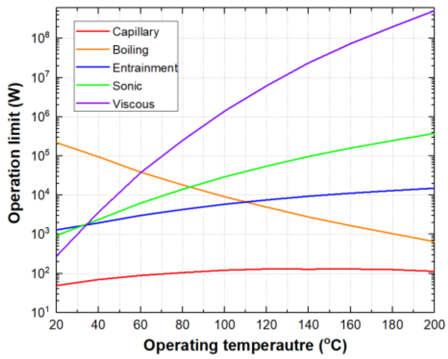

Fig. 3. Operation limits of heat pipe.

2. Heat pipe performance evaluation

There are various methods to evaluate the heat pipe performance and derive the optimum design. In this study, evaluation of operation limits and thermal resistance and heat transfer coefficient were performed to estimate the thermal performance of the heat pipe.

The operation limit is the maximum heat transfer capacity of the heat pipe. The operation limits (capillary limit, boiling limit, entrainment limit, sonic limit, and viscous limit) of the heat pipe were investigated with existing correlations referred from Kucuk [3] for 0.8 m long heat pipe, 2 layers of 100-mesh screen wick, use water as a working fluid and in horizontal condition. According to Fig. 3, the capillary limit shown to be the most dominant limit for overall operating temperature. The comparison of operation limit result was derived from theoretical calculation and experiments were conducted for certain operating temperature.

As the capillary limit determines the heat transfer capacity of the water heat pipe, the definition of capillary limit was used to predict the effect of heat pipe diameter variation. Capillary limit can be reached when the capillary pumping force derive from wick structure cannot overcome the overall pressure drop occurred in heat pipe as described in equation (1).

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

The capillary pumping force, vapor and liquid pressure drop are described in equation (2). The gravitational pressure drop term was neglected to reflect the zero-gravity condition. With the maximum heat transport in a heat pipe which can be obtained from the equation (3) where the $\dot{m}$ is the maximum flow rate and λ is the latent heat of vaporization, the mass flow rate inside the heat pipe described as equation (4). As mass flow rate increase, the amount of heat transport through the heat pipe will be enhanced which can be achieved for larger heat pipe diameter. Therefore, the experiments to estimate the effect of diameter variation will be conducted to achieve design optimization in aspect of heat pipe diameter.

$$\frac{2\sigma}{r_{eff}} \geq \frac{f_v \mathrm{Re}_v \mu_v}{2r_{hv}^2 A_v \rho_v \lambda} L_{eff} q + \frac{\mu_l}{KA_w \lambda \rho_l} L_{eff} q \quad (2)$$

$$q = \dot{m}\lambda \quad (3)$$

$$\dot{m} = \frac{2\sigma}{r_{eff}} \frac{1}{L_{eff}} \left(\frac{f_v \mathrm{Re}_v}{2r_{hv}^2 A_v^2 \rho_v} + \frac{\mu_l}{KA_w \rho_l} \right)^{-1} \quad (4)$$

3. Experimental setup

The heat pipe experimental setup includes heat pipe test section, 6 cartridge heaters, vacuum pump, power supply, cooling jacket as shown in Fig. 4. An experiment was conducted with 0.8 m long stainless steel 316L pipe with 25.4 mm outer diameter heat pipe. The detailed experimental conditions are described in Table. 1. Two layers of 100 screen wire mesh was used as a wick structure and the test section was filled with distilled water. The experiment was conducted with a horizontal orientation to reflect the zero-gravity condition in space. K-type thermocouples were installed along with the heat pipe axial position.

Two types of experiments were conducted to evaluate the operation limit and thermal performance of the heat pipe. The first experiment is divided into three parts: part 1: achieve steady state inside heat pipe by saturate the wick structure with vapor, part 2: heat pipe operation & operation limit evaluation, part 3: apply power by each step. The experimental procedure is as follows: (1) Fill the test section with working fluid; (2) Apply power to evaporator with cartridge heater until temperature of the evaporator and adiabatic section reaches to saturation condition and maintain steady temperature; (3) Increase power gradually for each step until the temperature of each section reaches to steady-

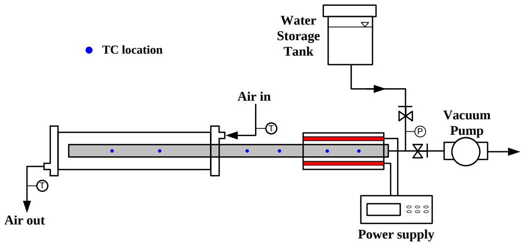

Fig. 4. Schematic diagram of heat pipe experimental setup.

Table I: Heat pipe experimental conditions.

Parameters	Value
Pipe material	SS316L
Working fluid	Water
Fill ratio (%)	100
Length ratio (evp:adi:con)	1:1:2
Heat load (W)	50-300
Orientation	Horizontal

state; (4) Cool the condenser section with compressed air. Adjust the mass flow rate of compressed air to maintain the adiabatic temperature steady for each power step in part 2. The second experiment was conducted with constant cooling condition for condenser section. The pressure of heat pipe evaporator section was measured with pressure gauge for each step to check the saturation temperature.

An experimental result with 1-inch heat pipe was be compared with theoretical operation limits calculation to investigate the thermal performance of the heat pipe. The additional experiment with various pipe diameter will be performed for further work.

4. Results and discussion

4.1 Heat pipe operation limit estimation

Fig. 5 shows the wall temperature distributions for each power step to evaluate the operation limit of the heat pipe. After the steady-state achieved in part 1, cooling in condenser section was started and the temperature of the adiabatic section was maintained constant as 104ºC which presents the saturation temperature of heat pipe. The capillary limit for operating temperature 104ºC was theoretically estimated as 140 W. From Fig. 6, as the power increase, the temperature difference between evaporator and adiabatic section also increase from 3-20ºC. Temperature of the condenser section decreases for increasing power input due to the increasing coolant flow to maintain the adiabatic section temperature.

According to Schmalhofer and Faghri [4], the capillary limit was defined when the wall temperature of the evaporator section exhibited a sudden temperature rise to 25ºC. As the temperature difference in evaporator and adiabatic section can be regarded as

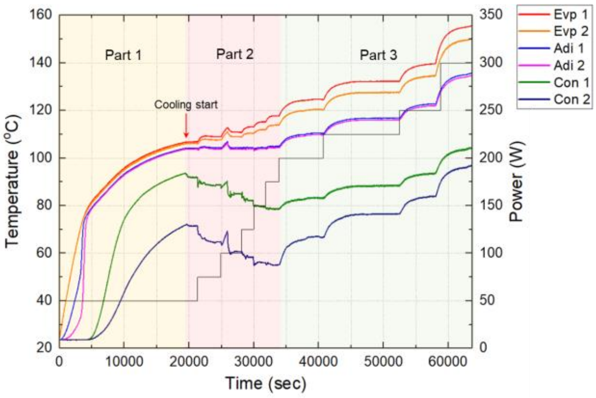

Fig. 5. Wall temperature histories of heat pipe according to heat loads.

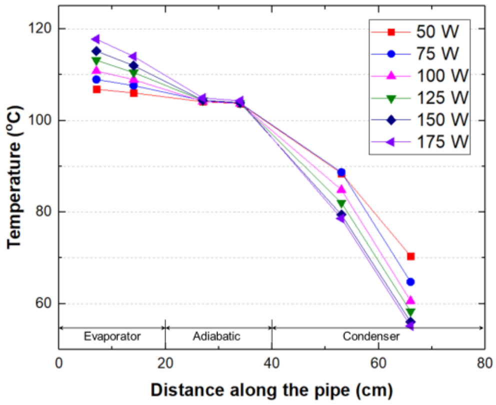

Fig. 6. Wall temperature distribution along the heat pipe for each power step.

wall superheat, heat pipe almost reaches to the capillary limit near the 175 W. However, the adiabatic temperature cannot maintain constant from 200W due to the lack of coolant flow.

The thermal performance of the heat pipe evaluated from the experiment showed higher result compared to theoretically estimated limit. From the result, it can be concluded that the heat pipe will operate safely above the target maximum heat transfer, showing higher performance than the theoretically calculated operating limit.

4.2 Heat pipe thermal performance evaluation

The second experimental results for wall temperature distributions at each steady state along the heat pipes according to the heat input is shown in Fig. 7. As heat load increases, the pressure inside the heat pipe increases which lead to increase of adiabatic section temperature that indicates the saturation temperature. For higher power input, a larger amount of heat transported from evaporator to condenser with phase change of the working fluid which leads to smaller temperature difference between the evaporator and condenser section.

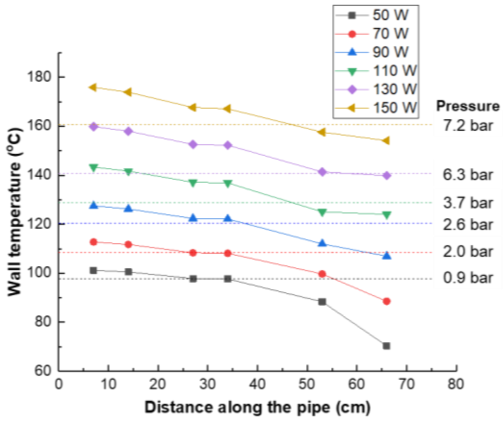

Fig. 7. Wall temperature distribution along the heat pipe for each power step.

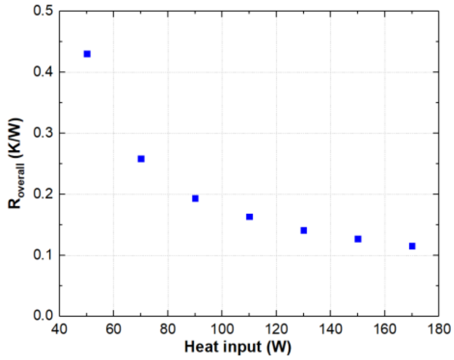

Fig. 8. Overall thermal resistance of heat pipe.

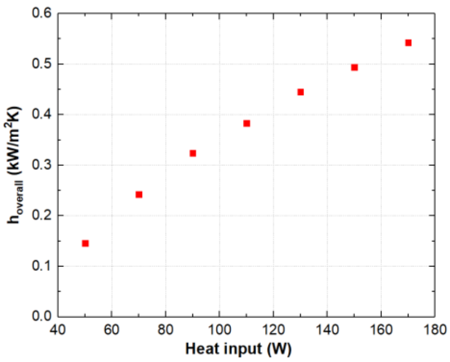

Fig. 8. Overall heat transfer coefficient of heat pipe.

Fig. 8 and 9 show the results of overall thermal resistance and heat transfer of the heat pipe which were investigated based on the measured wall temperature distributions using equations (5) and (6). For higher heat loads, thermal resistance decreases and heat transfer coefficient increases due to the decreasing temperature difference between evaporator and condenser section.

$$R = \frac{T_e - T_c}{Q} \tag{5}$$

$$h = \frac{q''}{(T_e - T_c)} \tag{6}$$

5. Conclusions

To achieve maximum power output for heat pipe cooled space nuclear reactor, design optimization of heat pipe should be conducted according to various design parameters. In this study, the affect of diameter variation was conducted to obtain optimum design by evaluate the operation limit and thermal performance of the heat pipe. The definition of capillary limit was used to predict the diameter effect for heat pipe capacity. It showed that the mass flow rate of heat pipe increases with larger diameter which lead to larger heat transfer capacity of heat pipe. For preliminary study, the experiment with 1-inch pipe was conducted and the experimental result was compared with theoretical estimated operation limit. The experimental operation limit showed higher value compared to the theoretical result. Further study will be performed with 1/2 inch and 3/4 inch test section to investigate the heat pipe performance affected by diameter variation.

ACKNOWLEDGEMENT

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NOMENCLATURE

A = area	[m^2]
P = pressure	[Pa]
R = thermal resistance	[K/W]
Re_v = Reynolds number of vapor	
T = temperature	[K]
K = permeability of the wick	[m^2]
L_{eff} = effective length of the pipe	[m]

Greek-letters

σ = surface tension	[N/m]
μ = viscosity	[Pa·s]
ρ = density	[kg/m^3]
λ = latent heat of vaporization	[J/kg]
ψ = tilt angle	[º]

Subscripts

c = condenser
cap = capillary
e = evaporator
eff = effective capillary radius
g = gravity
h = heat transfer coefficient
r = effective capillary radius
v = vapor

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