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Preliminary Evaluation of a Sodium Loop Heat Pipe Design using the Lumped Model

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1. Introduction

Microreactors are small nuclear reactors in the range of 1 to 20 MW in terms of thermal power and are being actively developed to replace diesel power generation [1]. Among these, microreactors that utilize heat pipes are receiving attention for their simplified primary heat transfer systems, which not only reduce their size and weight but also lower the probability of failure. The currently developed heat pipe-based microreactors utilize traditional cylindrical heat pipes, which wicks in the adiabatic section. However, the shape limitations of these cylindrical heat pipes lead to low design flexibility, as well as poor manufacturability and scalability [2,3]. On the other hand, loop-type heat pipes can design the evaporator and condenser section independently, and the absence of wicks in the adiabatic section eliminates machining constraints and overcomes issues caused by plugging. Therefore, loop-type heat pipes are expected to overcome the existing limitations of cylindrical heat pipes and have high design flexibility and superior operational limits in the design of large-capacity ground-based microreactors. So far, loop-type heat pipes using sodium as the working fluid have been studied in the field of solar power generation [4], but systematic design technology development and performance verification research for microreactor applications are lacking. In this study, a loop heat pipe design code was developed by improving the conventional cylindrical heat pipe design code using the lumped model, and a parametric study was conducted.

2. Methods

2.1 Concept of Loop Heat Pipe

Loop heat pipes (LHPs) distinguish themselves from cylindrical heat pipes by their structural design, featuring separate evaporator, adiabatic, and condenser sections with wicks exclusively in the evaporator. This deviation not only alters the wick's shape but also introduces unique structural characteristics. Specifically, the vapor and liquid in LHPs navigate through independent lines due to the distinct separation of the evaporator and condenser, marking a clear departure in design and function from their cylindrical counterparts.

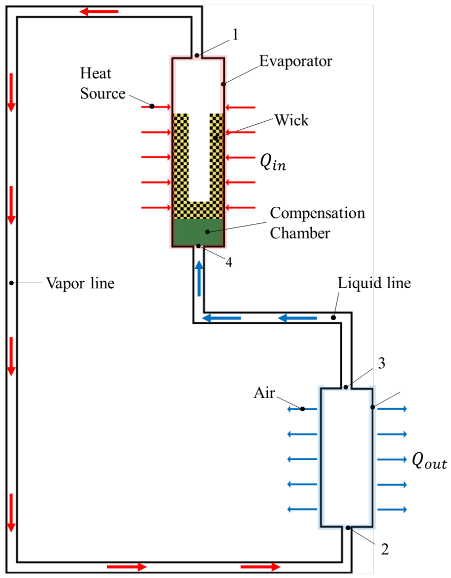

Fig. 1. Schematic drawing of a loop heat pipe.

2.2 Design Code for LHP

The design code was based on a steady-state analysis, and evaluated for a design that meets the requirements. It employed a fast computational method using the lumped parameter approach, which provides useful results with quick computation speeds. The backbone code utilized was originally developed for cylindrical sodium heat pipe by Korea Atomic Energy Research Institute (KAERI). It was modified to derive temperature distributions and operational limits based on the design parameters and operating conditions of a loop heat pipe.

In the code, the heat pipe employs a total of four temperature nodes. The heat source (Q_{in}) imposed on the external surface of the evaporator and the temperature of the condenser fluid (T_{cd}) are the boundary conditions. To consider the thermal resistances, a total of five equations are used according to the movement of the working fluid. Equations of thermal resistance at different positions are presented in Table I. In the condenser of the loop-type heat pipe that has no wick, only the thermal resistance between the interface and the shell and between the shell and the coolant is considered. In the equation, h_e represents the convective heat transfer coefficient at the evaporator's outer surface, h_c denotes the convective heat transfer coefficient of the coolant, r_s stands for the tube thickness, r_o represents the outer diameter of the tube, r_i stands for the inner diameter of the tube, k_s denotes the conductivity of the tube, k_l represents the conductivity of the working fluid at the interface, L_e represents the length of the evaporator, L_c represents the length of the condenser, and r_l represents the interface between liquid and vapor.

Table I: Thermal resistance calculation

Part	Location	Thermal Resistance
Evaporator	Outside to the shell	$\frac{1}{2\pi r_0 L_e}[\frac{1}{h_e}+\frac{\Delta r_s}{2k_s}]$
	Shell to the wick	$\frac{1}{2\pi r_i L_e}[\frac{\Delta r_s}{2k_e}+\frac{\Delta r_l}{2k_l}]$
	Wick to the interface	$\frac{1}{2\pi r_w L_e}[\frac{\Delta r_l}{2k_l}]$
Adiabatic section	Interface	negligible
	Vapor	negligible
	Interface	negligible
Condenser	Interface to shell	$\frac{1}{2\pi r_i L_c}[\frac{\Delta r_s}{2k_s}+\frac{\Delta r_l}{2k_l}]$
	Shell to coolant	$\frac{1}{2\pi r_0 L_c}[\frac{1}{h_c}+\frac{\Delta r_s}{2k_s}]$

A loop heat pipe does not have wicks in the adiabatic and condenser sections; instead, they feature relatively long lines connecting the evaporator and condenser. Considering these aspects, a code was developed to calculate the pressure drop. The flow rate of the liquid is very low ($Re_L \cong 248$), and the pressure drop caused by bends in the system is negligible.

The operational limits that define the performance of a heat pipe include the capillary limit, sonic limit, entrainment limit, boiling limit, and viscosity limit. However, the entrainment limit, which arises due to the presence of interfaces in the fluid flow within the heat pipe, does not apply to loop heat pipes because they lack interfaces in the operating fluid flow. This presents an advantage as the entrainment limit can be disregarded. The remaining operational limits were calculated following established methods.

3. Result

3.1 Design Result of the LHP

To analyze the characteristics of a Loop heat pipe (LHP) with a 1 kW heat load using code, an LHP was designed as shown in Table II. The design opted for a short liquid line and a long vapor line to minimize the amount of sodium. Additionally, the evaporator employs a hybrid wick combining an annulus and a sintered wick.

Table II: Dimension of the loop heat pipe.

Item	LHP
Evaporator Length (m)	0.25
Vapor line length (m)	1.2
Liquid line length (m)	0.3
Condenser length (m)	0.25
Evaporator OD (m)	0.0254
Vapor line OD (m)	0.01
Liquid line OD (m)	0.00635
Condenser OD (m)	0.0254
Thickness (m)	0.0012
Annulus wick porosity	0.99992
Sintered wick porosity	0.32

3.2 Design Evaluation

The coolant inlet temperature (T_{cd}) was set as the main operating condition. Changing this temperature modifies the operating temperature, and consequently, the values of the operation limits also change. As shown in Table III, it has been observed that as the temperature increases, the capillary limit, sonic limit, and viscous limit increase, while the boiling limit decreases. This phenomenon is attributed to the temperature-sensitive density characteristics of sodium. Therefore, when conducting actual experiments, it is crucial to focus on the boiling limit and set an appropriate operating temperature.

Table III: Operational temperature (T_{op}) and limits at 1 kW with changes in condenser inlet temperature (T_{cd}).

Temp. (K)		Operational Limits (W)			
T_{cd}	T_{op}	Capillary	Sonic	Boiling	Viscos
703	690	5434	2224	264641	13188
713	700	5756	2519	234600	16892
723	710	6088	2846	208480	21521
733	720	6430	3206	185709	27281

Table IV shows a comparison of the operating limits of cylindrical and loop heat pipes under the same temperature and power conditions. Cylindrical heat pipes (CHP) have higher operation limits compared to loop heat pipes (LHP) in other aspects, but the entrainment limit value is significantly lower, making it more likely to be the first limiting factor in operation, thus requiring careful consideration. However, by using loop heat pipes, there is an advantage in that the entrainment limit fundamentally does not need to be considered.

Table IV: Compare the operating limits of a cylindrical heat pipe (CHP) and a loop heat pipe (LHP) for the same temperature and power conditions.

Operation condition	CHP	LHP
Power (kW)	1.0	1.0
T_{cd} (K)	703	703
T_{op} (K)	770	690
Capillary limit (W)	27,310	5,434
Sonic (W)	19,985	2,224
Boling (W)	1,164,676	264,641
Viscos (W)	677,896	13,188
Entrainment (W)	4,527	none

4. Conclusion

1. This study utilized a one-dimensional design code to conduct a steady-state analysis of alkali loop heat pipes for microreactors and compared the operating limit characteristics with cylindrical heat pipes.
2. Under the same temperature and power conditions, cylindrical heat pipes show higher values for most operating limits than loop heat pipes but have a significantly lower entrainment limit. In contrast, loop heat pipes have the advantage of not needing to consider the entrainment limit.
3. In future work, based on these analytical results, we plan to establish an experimental facility and evaluate the practical applicability of new designs.

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