Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2023

Design Guide for Water Heat Pipes for Nuclear Power Plant Applications Based on the Thermal Limit Evaluation

Ye Yeong Park and In Cheol Bang*,
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*

1. Introduction

Heat pipes have been widely used in various industries such as electronic devices and aerospace, due to their efficient heat transfer performance without requiring external power, simple design, and lightweight. Incorporating heat pipes in nuclear power plants has been considered an innovative solution that can provide several advantages, including passive heat transfer performance, zero-gravity operation with capillary pumping force, and elimination of pumps, which can achieve a simplified reactor design and enhanced safety. Several studies have been conducted to apply heat pipe or thermosyphon without a wick structure to the nuclear reactor systems to achieve passive decay heat removal. For example, Y. Kuang et al. [1] conducted an experiment with a large-scale separate ammonia heat pipe used for passive cooling of the spent fuel pool and proposed a numerical model. Additionally, the hybrid control rod heat pipe was proposed by Y. S. Jeong et al. [2] and K. M. Kim et al. [3] which contains neutron absorber material in the evaporator section for passively cooling the spent nuclear fuel dry storage cask.

The successful application of heat pipe for the nuclear industry relies on efficient and passive heat removal from the heat source to the heat sink. However, unlike previous studies related to heat pipes mainly apply to small heat transfer systems, the size of heat pipes must be increased to apply them to nuclear power plant systems. In addition, studies have mainly focused on the application of thermosyphon to nuclear reactor systems that do not include wick structures that can operate only in a vertical direction. Therefore, optimizing the design of heat pipes on a larger scale is essential for ensuring the safe and efficient operation of nuclear reactors. The design process of heat pipes involves the selection of various design parameters, such as working fluid, diameter, wick structure, and length, which determine the thermal limit of the heat pipe.

The thermal limit of the heat pipe, also known as an operation limit, is the amount of maximum heat transfer achievable at each operating temperature without experiencing dry-out, which can impede the heat transfer function of the heat pipe. Therefore, evaluating the operation limit of a heat pipe is crucial for accurately predicting the thermal limit of a nuclear reactor system and ensuring the safety margin of the heat transfer system.

This paper presents a design guide for water heat pipes in nuclear power plant applications, based on the results of the thermal limit evaluation with respect to various design parameters such as length, diameter, and wick type. The proposed heat pipe design guidelines can serve as an important criterion in the design process of a passive cooling system that incorporates heat pipes for nuclear power plant applications.

2. Thermal limit of the heat pipe

The maximum heat transfer amount of a heat pipe is determined by several operation limits, including the capillary limit, viscous limit, sonic limit, entrainment limit, and boiling limit. The design factors that can affect each of these limits include the diameter, wick structure, length, operating temperature, and type of working fluid. Understanding the effect of each design parameters on the operation limit is important when predicting the power output or overall size of nuclear reactors.

Among the several operation limits, the capillary, entrainment and boiling limit can significantly limit the heat transfer function of the heat pipes by causing the dry-out in the evaporator section. The capillary limit occurs when the capillary pumping force induced in the wick structure cannot overcome the pressure drop that occurs in axial directions. The boiling limit occurs when the radial heat flux applied to the evaporator exceeds the limit, causing bubbles to form at the heated surface and block the working fluid’s circulation. Additionally, when the heat applied to the evaporator increases, the vapor flow can cause liquid to flow into the vapor section, thereby interfering with the circulation of the working fluid, which is called an entrainment limit.

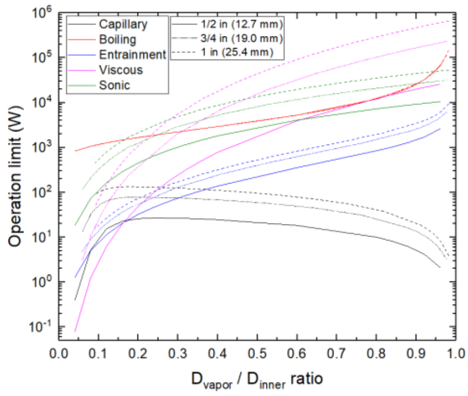
To understand the effect of each design variable on the thermal limit and to provide overall design guidelines for the application of heat pipes in nuclear reactor, each operation limit was evaluated according to diameter, length, and wick type. Water with operating temperature of 80^{o}C was selected as a working fluid for the heat pipe thermal limit evaluation. The correlations used for heat pipe thermal limit calculation are listed in Table I.

2.1 Selection of the heat pipe diameter

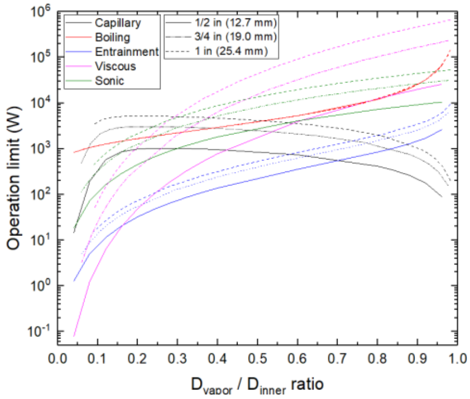
The diameter of the heat pipe is an important design factor determines the heat transfer capacity. Optimizing the heat pipe diameter involves finding a balance

Table I: Correlations used for heat pipe thermal limit calculation [4]

Limit	Correlation
Capillary limit	$Q_{capillary} = \dfrac{\dfrac{2\sigma}{r_{eff}} - \rho_l g \cos\psi d_v - \rho_l g \sin\psi L_{eff}}{\left(\dfrac{f_v \mathrm{Re}_v \mu_v}{2r_{hv}^2 A_v \rho_v \lambda} + \dfrac{\mu_l}{K A_w \lambda \rho_l}\right) L_{eff}}$
Boiling limit	$Q_{boiling} = \left(\dfrac{2\pi L_{evp} k_{eff} T_v}{\lambda \rho_v \ln(r_i / r_v)}\right)\left(\dfrac{2\sigma}{r_n} - \Delta P_{capillary}\right)$
Entrainment limit	$Q_{entrainment} = A_v \lambda \left(\dfrac{\sigma \rho_v}{2r_{hw}}\right)^{1/2}$
Sonic limit	$Q_{sonic} = A_v \rho_v \lambda \sqrt{\dfrac{\gamma_v R_v T_v}{2(\gamma_v + 1)}}$
Viscous limit	$Q_{viscous} = \dfrac{A_v r_v^2 \lambda \rho_v P_v}{16 \mu_v L_{eff}}$



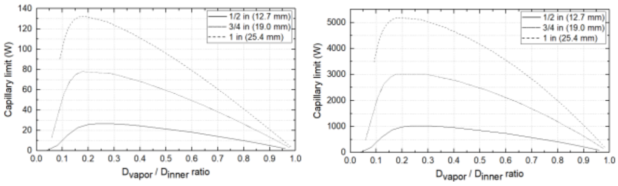
(a) Horizontal



(b) Vertical

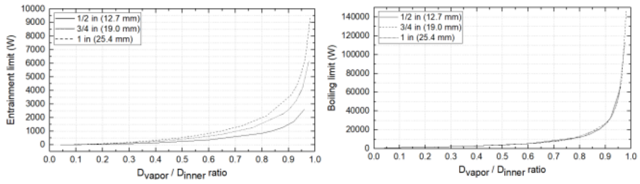
Fig. 1. Operation limits of the heat pipe according to the D_v/D_i ratio for horizontal and vertical orientation conditions.

between the required heat transfer capacity and the available space within the reactor systems. The diameter of the heat pipe can be determined by two factors: the diameter of the container pipe and the thickness of the wick structure located on the inner wall of the pipe. The thickness of the wick structure determines the flow area of the condensed working fluid transported from the condenser to the evaporator section and also determines the flow area of the vapor diameter. The diameter of the vapor flow path affects the amount of vapor transport from the evaporator to the condenser section which is calculated by subtracting twice the wick thickness from the inner diameter of the container pipe as shown in equation (1). For the same length of heat pipe, the heat pipe with larger vapor diameter can transfer more amount of heat from the heat source.

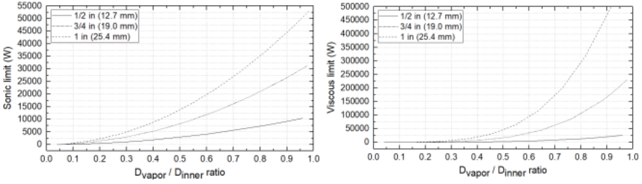


(a) Horizontal (b) Vertical

Fig. 2. Capillary limit of the heat pipe according to the D_v/D_i ratio for horizontal and vertical orientation conditions.

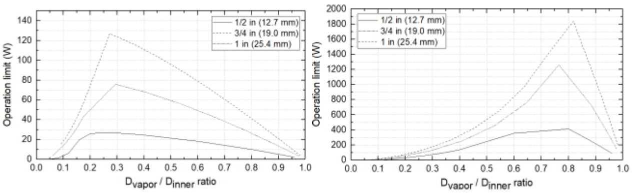


(a) Entrainment limit (b) Boiling limit



(c) Sonic limit (d) Viscous limit

Fig. 3. Entrainment, boiling, sonic, and viscous limit of the heat pipe according to the D_v/D_i ratio for horizontal and vertical orientation conditions.



(a) Horizontal (b) Vertical

Fig. 4. Maximum heat transfer limit of the heat pipe according to the D_v/D_i ratio.

$$D_v = D_i - 2t_{wick} \tag{1}$$

Therefore, to evaluate the effect of both wick structure thickness and the vapor diameter, the operation limits were evaluated in terms of the vapor diameter (D_v) to the inner diameter of the pipe (D_i) ratio. For the calculation, #100 screen mesh was used as a wick structure.

Fig. 1. ~ 4. shows the result of the calculations based on the D_v/D_i ratio. Overall, as the outer diameter of the container increases from 1/2 inch to 1 inch, the operation limit of the heat pipe also increases due to the

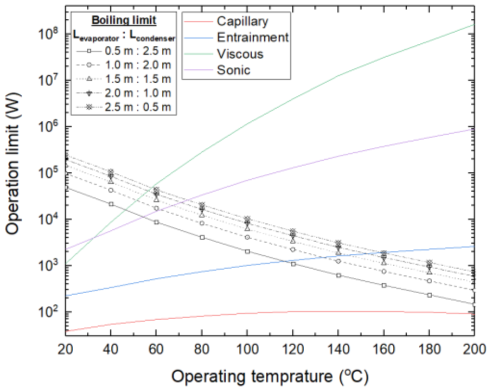
larger vapor flow area. As shown in Fig. 1, in the horizontal orientation, the capillary limit acts as an influential factor that determines the thermal performance of the heat pipe for the overall D_v/D_i ratio range. However, in the case of vertical orientation, the entrainment limit should be considered as an important factor. Therefore, depending on the installation angle of the heat pipe in the nuclear reactor system, different types of operation limit should be considered.

Moreover, in Fig. 2, as the D_v/D_i ratio increases, the thermal limit of entrainment, sonic, viscous and boiling limits increases due to the increased vapor flow area. However, at the same time, the liquid flow area decreases due to the reduced wick structure thickness, resulting in the decrease in the capillary limit as shown in Fig. 3. The operation limit results shown in Fig. 4. indicate that depending on the application system, a smaller D_v/D_i ratio with a larger wick thickness should be selected for horizontal installation, where capillary pumping force is important. In contrast, a larger D_v/D_i ratio should be selected in vertical conditions to increase the overall operation limit with increased vapor flow area.

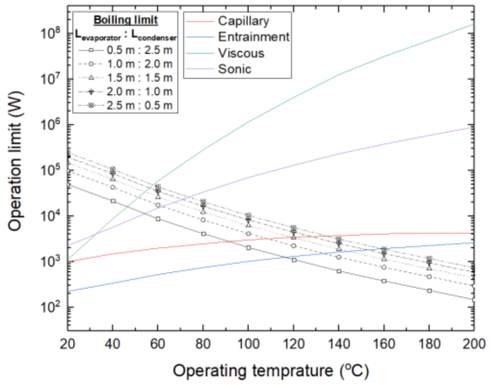
2.2 Selection of the heat pipe length

The length of the heat pipe is determined by the distance between the heat source and the heat sink. A longer heat pipe can be applied in large systems such as nuclear industries to transfer heat over greater distances, but it may experience higher flow resistance, which can reduce the heat transfer efficiency of the heat pipe. The heat pipe can be divided into three parts; evaporator, adiabatic, and condenser sections. Among these three parts, the length of the evaporator section significantly affects to determination of the boiling limit. For a shorter evaporator section, the radial heat flux increases for the same heat input and the bubble generated at the heated surface can block the porous of the wick structure, which can cause dry-out. Fig. 5 shows the effect of length ratio ($L_{evaporator}$: $L_{adiabatic}$: $L_{condenser}$) of the heat pipe on the operation limit. For the calculation, the length of the adiabatic section was fixed as 1m, and the total length of the heat pipe was adjusted as 4m. For the same total length, the capillary, entrainment, viscous and sonic limit is not affected by the change in length ratio. However, the boiling limit decreases as the length of evaporator section decreases due to the high radial heat flux. Especially when the heat pipe is applied in vertical condition, and target operating temperature is above 110ºC, the thermal limit of the heat pipe can be limited by the boiling limit due to the short evaporator section length. Based on the result, securing enough length of the evaporator section can enhance the boiling limit. The effect of the total length on the operation limit is described in the Section 2.3 in combination with the effect of the wick type.

2.3 Selection of wick structure type

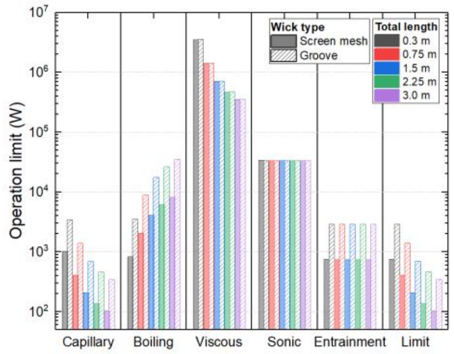


(a) Horizontal

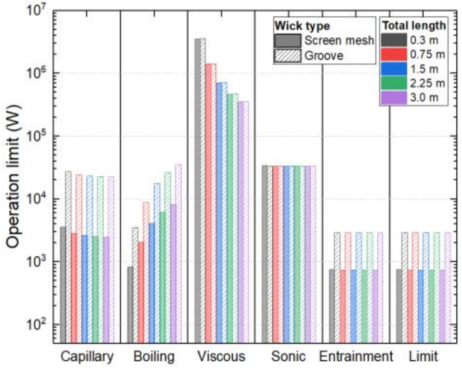


(b) Vertical

Fig. 5. Operation limit according to the various length ratio in horizontal and vertical orientation.



(a) Horizontal



(b) Vertical

Fig. 6. Operation limits according to the wick type and the total length of heat pipe for horizontal and vertical orientation conditions.

The wick structure of the heat pipe is designed to facilitate capillary pumping action and enable the circulation of the working fluid even in the absence of gravity. The selection of a wick structure depends on various factors, including the required capillary pumping force, heat transfer rate and distance between the heat source and heat sink. Commonly used conventional heat pipe wick structures include the screen mesh wick, groove wick, sintered wick or annulus wick. For example, a sintered metal wick or screen mesh wick may use for applications requiring high capillary pumping forces, such as transportable modular reactors, while a grooved wick having low flow resistance may be suitable for long-distance heat transportation applications such as space radiator. Among various wick types, the #100 screen mesh wick with 12 layers and the optimized groove wick was compared in this study according to the wick type and the total heat pipe length as shown in Fig. 6.

The results showed that the groove wick outperformed the screen mesh wick for both horizontal and vertical conditions as shown in Fig. 6. Since the optimized designed groove wick was used for the calculation, it exhibited a higher thermal limit compared to the screen mesh wick.

In horizontal condition, the heat pipe performance for both screen mesh and groove wick are limited by the capillary limit. As the heat pipe length increases, the capillary limit decreases due to the increased axial pressure drop. On the other hand, in the vertical condition, the maximum heat transfer rate is determined by the entrainment limit, which is not affected by the total length of the heat pipe.

Therefore, for nuclear power plant applications that require long-distance heat transport, the groove wick offers high permeability and effective thermal conductivity, making it a suitable wick structure. However, when considering the use of the groove wick for the horizontal conditions, incorporating a smaller radius wick structure in the evaporator section can enhance the capillary limit by increasing the capillary pumping force.

3. Conclusion

The optimal design of heat pipes must be carefully considered to ensure efficient heat transfer and to meet the specific requirements of nuclear reactor applications. This study provides a comprehensive overview of the optimization process of heat pipe design for nuclear reactor applications. The thermal limits evaluation results conducted according to the various diameter, length, and wick type provides information on the design factors affecting each operation limit and offers overall design recommendations for heat pipe installation conditions.

The larger diameter of the heat pipe can transport more heat from the heat source, and therefore the sufficient vapor area should be secured Also, the wick structure should have enough thickness to provide a liquid flow path in the wick structure, therefore the optimal D_v/D_i ratio should be selected according to the installation environment. As the total length of the heat pipe increase, the axial pressure drops increase which eventually reduce the capillary limit. However, if the length of the evaporator is too short, increasing radial heat flux may limit the operation of the heat pipe due to the boiling limit. Since long-distance heat transfer is required in nuclear industries, the wick structure capable of overcoming axial pressure drop should be applied and a sufficient length of the evaporator is required. The groove wick can be selected as a wick structure having lower flow resistance and transfer heat over a long distance, but the additional design process of optimal groove wick should be conducted to achieve sufficient vapor flow space to prevent the entrainment limit.

The results of this study can be helpful in deriving the optimal design of heat pipes, which can contribute to the enhanced safety and efficiency of the passive cooling system in nuclear power plants.

ACKNOWLEDGEMENT

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No.2021M2D2A1A03048950).

REFERENCES

[1] Y. Kuang, Q. Yang, W. Wang, Thermal analysis of a heat pipe assisted passive cooling system for spent fuel pools, International Journal of Refrigeration, Vol. 135, p.174-188, 2022.

[2] Y. S. Jeong, K. M. Kim, I. G. Kim, I. C. Bang, Hybrid heat pipe-based passive in-core cooling system for advanced nuclear power plant, Applied Thermal Engineering, Vol. 90, p.609-618, 2015.

[3] K. M. Kim and I. C. Bang, Effective energy management design of spent fuel dry storage based on hybrid control rod-heat pipe, International Journal of Energy Research, Vol. 45, p.2160-2176, 2020.

[4] A. Bejan, A. D. Kraus, Heat Transfer Handbook, John Wiley & Sons, 2003.