Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 26-27, 2023

Experimental study of two-phased thermosyphon under extreme conditions for nuclear power plant applications

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

***Keywords :** Thermosyphon, Passive heat transfer system, Loss of cooling capacity, Horizontal operation,

1. Introduction

The application of two-phased heat pipe /thermosyphon in the nuclear industry has emerged as a promising solution to address key challenges associated with thermal management and passive cooling systems. The operation of a two-phased heat pipe/thermosyphon is based on natural convection and the phase change of a working fluid which relied on gravity and buoyancy forces to facilitate the heat transfer within the system.[1] As it can passively transfer heat without external pumps or power, thermosyphon/heat pipe has been emphasized as a key component of the heat transfer system, especially in the nuclear power plant. The thermosyphon can be applied in systems such as passive spent fuel pool cooling and decay heat removal to prevent overheating and ensure long-term safety.[2,3] Before implementing thermosyphons in nuclear power plant systems, it is crucial to investigate their operational behavior, especially under extreme accident scenarios such as sudden changes in orientation or heat sink loss.

In a thermosyphon, gravity plays a significant role in maintaining a continuous and efficient circulation of the working fluid. As the working fluid at the evaporator absorbs heat from the heat source, the generated vapor is transported to the condenser section due to the buoyancy forces. The condensed vapor at the condenser section is transported back to the evaporator with the gravity force.

In the case of transportable micro-reactors or rollover accidents of the system, the evaporator and condenser section are located at the same elevation. In such scenarios, this alignment can result in a lack of height difference for gravity-driven natural circulation and only rely on the density difference caused by the temperature gradients of the working fluid. Consequently, the circulation of the working fluid becomes slower, leading to less efficient heat transfer compared to the vertical orientation due to the weaker natural circulation forces.

If the cooling capacity of the thermosyphon condenser is reduced, it can lead to several potential consequences. The condenser of the thermosyphon is responsible for dissipating heat from the system, so any reduction in its cooling capacity can negatively impact the overall performance and the safety of the system. With reduced cooling capacity, the thermosyphon cannot remove heat from the system and as a result, the operation temperature of the system will rise, potentially exceeding the desired or safe operating limits. When the evaporate working fluid cannot release heat at the condenser and the working fluid cannot return to the evaporator, overheating can occur near the heat source of the thermosyphon.

In this study, the experimental study was conducted to investigate the operational behavior of the thermosyphon, under extreme accident scenarios such as sudden changes in orientation or heat sink loss for application for passive heat transfer systems in nuclear power plants. The experiment was conducted according to the orientation, filling ratio, and cooling capacity of the thermosyphon.

2. Experiment

2.1 Experimental Setup

A large-scale heat pipe/thermosyphon test facility was constructed to provide a database of the operation phenomena of thermosyphon for extreme conditions, as depicted in Fig. 1. The test facility comprises a test section with a length ratio of evaporator : adiabatic : condenser sections as 2m : 1m: 1m. The evaporator section is equipped with a furnace heater covering a 2m length. The cooling jacket with a 1m length is located at the condenser section which allows for forced air cooling. To minimize heat loss, the test section is surrounded by an insulator along its entire length.

Twenty K-type thermocouples are attached along the axial direction at the outer wall of the test section to measure the temperature distribution under different experimental conditions. The orientation of the test section can be adjusted from a horizontal(0^{o}) to a vertical(90^{o}) position, enabling the evaluation of the performance of the thermosyphon for various system applications. The filling ratio of the thermosyphon is determined by the ratio of the working fluid volume to the volume of the evaporator. For the experiment, three different thermosyphon test sections were prepared with filling ratio of 0%, 50%, and 100%, where a filling ratio of 0% indicates a bare pipe without any working fluid.

The experimental conditions are listed in Table. I. To conduct the experiment, firstly, fill the thermosyphon with distilled water to achieve the target filling ratio. Next, using the vacuum pump, remove the noncondensable gas inside the test section. Adjust the orientation of the test section as required. Gradually

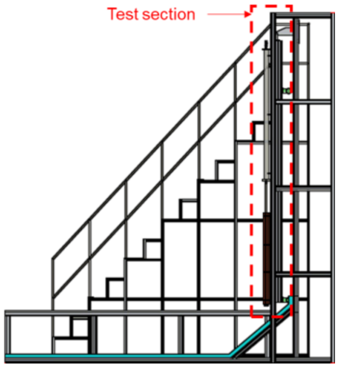


Fig. 1. Schematic of large-scale heat pipe/thermosyphon test facility.

Table I: Large-scale thermosyphon experimental conditions

Parameter	Value
Test section length	4.0 m (E:A:C = 2:1:1)
Test section diameter	25.4 mm
Working fluid	Distilled water
Test section material	Stainless steel 316L
Filling ratio	0%, 50%, 100%
Inclination angle	Horizontal, Vertical
Heater temperature	150, 200, 250
Flow rate of forced air	200 lpm, 40 lpm

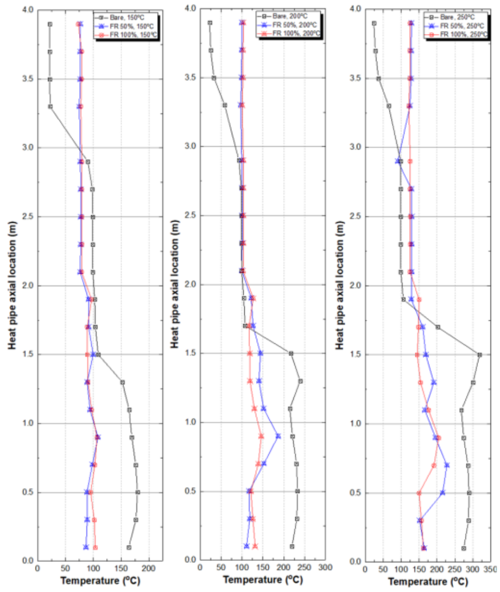
apply the heat through the furnace heater while providing a constant flow of forced air through the cooling jacket.

3. Results and Discussion

The experimental results obtained from various orientations, filling ratios, and cooling capacities were analyzed in terms of the temperature distribution and heat removal rate of the thermosyphon.

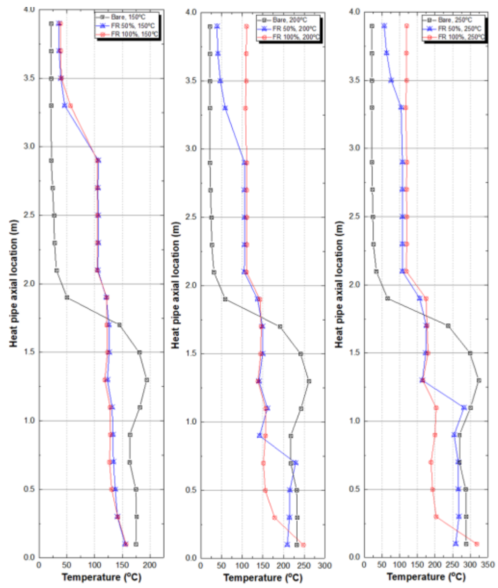
3.1 Orientation of the thermosyphon

Fig. 2 and 3 showed the axial temperature distribution results for the thermosyphon in both vertical and horizontal positions with different filling ratios. In the case of the bare pipe, a considerable temperature difference between the evaporator and condenser section was observed as the heat from the heat source only transferred through the conduction through the pipe and air inside the bare pipe. However, the thermosyphon with a filling ratio of 50% and 100% exhibits uniform distribution along the axial direction where the heat transfer through the latent heat and natural circulation of the working fluid leads to efficient heat transfer and prevents the drastic temperature rise at the evaporator section.



(a) (b) (c)

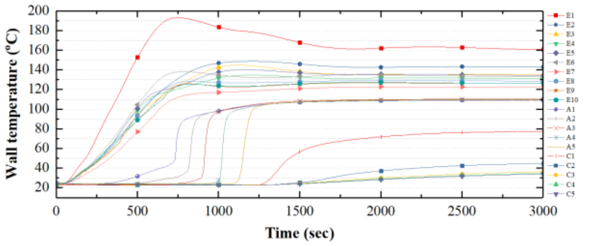
Fig. 2. Axial temperature distribution result for vertical position (a) T_{heater} = 150°C (b) T_{heater} = 200°C (c) T_{heater} = 250°C



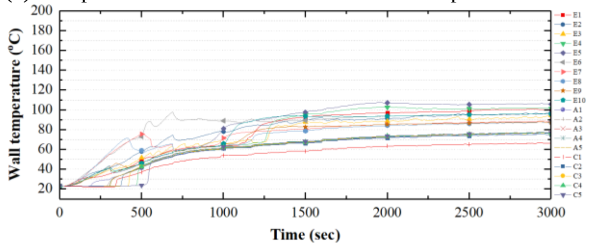
(a) (b) (c)

Fig. 3. Axial temperature distribution result for horizontal position (a) T_{heater} = 150°C (b) T_{heater} = 200°C (c) T_{heater} = 250°C

Regarding the outer wall temperature distribution, the vertical and horizontal cases exhibit different results. The vertical position showed nearly uniform temperature along the evaporator, adiabatic, and condenser sections for each heat input. As the temperature of the heater increased, the operating temperature, which could be represented by the adiabatic temperature, increased but at the same time, the uniformity of the temperature distribution was maintained.



(a) Temperature histories result for horizontal position



(b) Temperature histories result for vertical position

Fig. 4. Comparison of temperature distributions results.

For the horizontal case, uneven temperature distribution was observed which could result in a hotspot in the evaporator section. This non-uniformity was observed due to a reduced thermal center difference between the heat source and heat sink, resulting in a weakened driving force for natural circulation. Consequently, the condensed working fluid at the condenser section may not be sufficiently transported back to the evaporator, leading to a sudden temperature spike under high heat input conditions.

The start-up time of the thermosyphon is also an important evaluation parameter since the heat should be transferred quickly in the event of extreme conditions. As shown in Fig. 4, The start-up time for horizontal thermosyphon was longer compared to the vertical position. The thermosyphon is considered to be fully operational when the evaporated working fluid is heated and circulated throughout the test section, and temperature uniformity has been achieved.

Under horizontal conditions, the temperature of the evaporator increases significantly before the thermosyphon is fully operational. The slower activation of the condenser is due to the reduced driving force for working fluid circulation. In contrast, for the vertical condition, the heated vapor can easily reach the condenser section, enabling a faster start-up process without sudden spikes in the evaporator section.

Based on the results, the thermosyphon demonstrated superior performance when operated in a vertical position compared to horizontal in terms of temperature uniformity and start-up time. However, even in the event of a system rollover causing a shift to a horizontal orientation, the thermosyphon is still capable of maintaining steady heat removal performance under low heat input conditions.

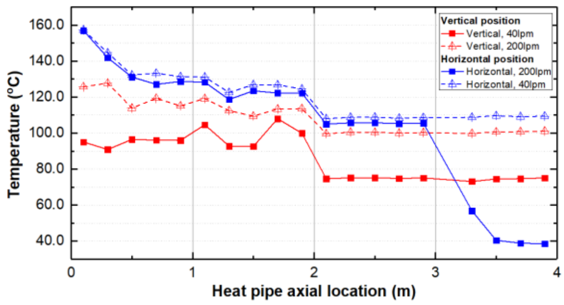


Fig. 5. Axial temperature distribution comparison for different cooling capacity and the orientation.

2.2 Loss of cooling capacity of the thermosyphon

An experiment was conducted to observe the operational behavior of the thermosyphon when its heat sink cooling capacity was reduced. The flow rate of the forced air through the cooling jacket was adjusted from 200lpm to 40lpm to simulate the loss of heat sink of the thermosyphon. In Fig. 5, the temperature distribution for the loss of heat sink condition was compared when the thermosyphon placed in horizontal and vertical position where having same filling ratio of 100%.

Under vertical conditions, the temperature distribution along the adiabatic and condenser sections remains almost uniform for both cooling conditions. However, the reduced heat removal through the condenser section causes an increase in operating pressure, resulting in higher operating temperatures and an overall shift in the temperature distribution. Despite a decrease in the heat removal rate from 71.5 W at 200 lpm to 59.1 at 40 lpm, the system is still capable of effectively removing heat without experiencing dry-out in the evaporator section.

For the horizontal position, under the same heater temperature input, the evaporator and adiabatic sections showed higher temperatures compared to the vertical orientation, due to the inadequate driving force for working fluid circulation. In the case of 200 lpm cooling, the condenser section temperature was significantly low, leading to the formation of a liquid pool due to slow fluid circulation. This resulted in reduced effective heat transfer area and inactivation of a certain portion of the condenser section, leading to a low heat removal rate of 26.8 W.

After reducing the cooling capacity to 40 lpm, the increase in temperature of the evaporator and adiabatic sections remained relatively constant compared to the vertical orientation. However, the condenser temperature increased, achieving better temperature uniformity throughout the thermosyphon and resulting in an increased heat removal rate of 34.8 W. This can be attributed to the generation of less condensed working fluid, thus reducing the inactive condenser section caused by the liquid pool.

Based on these results, for extreme conditions requiring the thermosyphon to transfer heat in a horizontal position, it is recommended to reduce the cooling capacity to prevent the formation of liquid pool in condenser section.

4. Conclusions

In this study, the experimental study was conducted to investigate the operational behavior of the thermosyphon, under extreme accident scenarios such as sudden changes in orientation or heat sink loss for application for passive heat transfer systems in nuclear power plants

The vertical position exhibit faster start-up and uniform temperature distribution without hot-spot compared to the horizontal position. For reduced cooling capacity, the operating temperature was increased and heat removal rate was reduced. In case of horizontal position, the temperature of the temperature difference between the evaporator and condenser section was large due to the lack of working fluid circulation driving force with reduced thermal center difference. However, it showed better heat removal rate and temperature distribution in reduced cooling capacity due to the less generation of the liquid pool in condenser section.

To address the heat transfer performance issues of the thermosyphon in horizontal orientation, especially during sudden accident conditions, the implementation of a wick structure will be proposed for future works. By incorporating the wick structure, the heat transfer efficiency of the thermosyphon in horizontal orientations can be greatly improved by providing capillary driving force for working fluid circulation without the need for gravity-driven force.

ACKNOWLEDGEMENT

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

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