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

PX : Asymmetric two-step thermosiphon for the containment cooling of SMR

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1. Introduction

The concept of a thermosiphon is a heat exchange method that performs heat transfer by natural convection accompanied by a phase change in a closed loop, and is currently widely used in industrial fields. The circulation mechanism of the working fluid in the closed loop is natural convection, which occurs because of the difference between the low density in the high temperature region and the high density in the low temperature region. Among the cases of the heat transfer mechanism by natural convection caused by different densities, the case with a phase change was the most effective. Figure 1(a) shows several types of natural convection accompanied by phase changes. The heat transfer mechanism by two-phase natural convection can be classified into two types of thermosiphons. First, the effect of surface tension (σ) was larger than the effect of gravity (g), whereas the other was the reverse.

First, a thermosiphon, in which the gravity effect is negligible, is classified as a general heat pipe composed of a single channel [1, 2] and a pulsating heat pipe composed of multiple channels [3]. These have been used in relatively small-scale heat exchanger devices. Here, the pulsation heat pipe generates an oscillatory flow forward and backward in the flow direction; however, it has a better heat transfer rate than a single-channel heat pipe.

The second method, in which the influence of gravity is dominant, is divided into single-step thermosiphons by single channel (O-loop) and multi-step thermosiphons by multi channel. Single-channel single-step thermosiphons have been widely used in large-scale heat transfer devices with heights of several meters. In this study, research was conducted on a two-step thermosiphon (X-loop) that is easy to apply in practice as a kind of multi-step thermosiphons. In addition, it exhibited superior heat transfer rate compared to the other three methods, as shown in Figure 1. Theoretical and computational methods were employed to verify the heat transfer mechanism.

As shown in Figure 1(b), the difference between the two types of gravity-dominant thermosiphons is that boiling and condensation occur once in a single channel, whereas in multi channel, boiling and condensation occur sequentially several times in one circulation.

Accordingly, it can be seen that the multi channel thermosiphon has a better heat transfer performance than the single-channel thermosiphon, as in the heat pipe heat transfer mechanism, which was verified in this study. In addition, a modified asymmetric two-step thermosiphon termed PX was introduced as a passive infinite cooling concept [4] for the containment cooling of small modular reactor (SMR).

2. PX: Asymmetric two-step thermosiphon

From the calculation results, the heat-exchange capacity of the X-loop was four times greater than that of the O-loop, and that of the PX-loop was between 2 and 4. However, from the viewpoint of structural integrity, the PX concept is expected to be more advantageous than the X-loop because there is no oscillation during the heat exchange. Because the PX concept, which has superior heat transfer performance compared to the O-loop, has never been introduced in the thermal engineering field, it has not yet been applied in the industry. Therefore, in this study, an SMR is recommended as one of the most effective applications. In the SMR, a containment vessel [9] is installed to isolate the reactor in the case of an accident. Because the containment vessel not only protects the reactor from external hazards, but also removes the residual heat of the reactor core after reactor shutdown, the containment vessel plays a significant role in both safety and structural aspects.

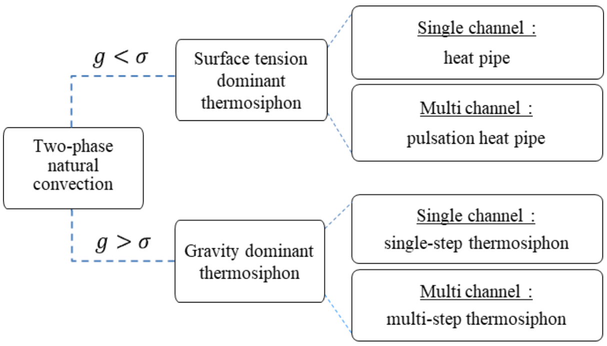
The types of containment vessels may have a structure that utilizes the O-loop concept, as shown in Figure 2, or the PX-loop concept in Figure 3(a). In both circulation concepts, steam is condensed on the inner wall of the containment vessel, and the condensed water subsequently flows into the reactor. Subsequently, the water is converted to steam by heating at the core and eventually discharged through the upper valve of the reactor. This heat transfer mechanism is similar for both concepts; however, the O- and PX-loops are clearly distinguished between the depending on the mechanism by which the discharged steam is cooled on the inner wall of the containment vessel.

The reactor in Figure 3(a) is of the same type as that in Figure 2, and shows the steady state of the SMR. Figure 3(b) shows the overall behavior in which the reactor was shut down owing to an accident, and then the residual heat of the core was discharged to the external pool through the residual-heat removal (RHR) pipe. Figure 3(c) shows the local thermohydraulic phenomena in this case.

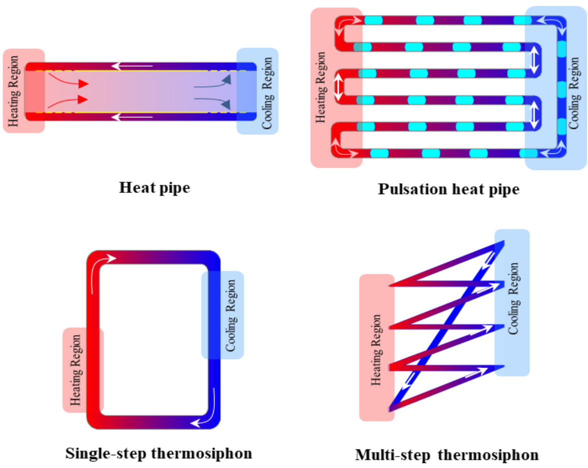
To verify this circulation phenomenon, a preliminary analysis was performed [6, 7] and the results confirmed that the circulation flow was well formed within the expected range. The containment vessel with the PX concept is fundamentally different from previous containment vessels of existing SMRs, which are currently being developed worldwide.

First, it can have the smallest containment volume per reactor power owing to its excellent heat-exchange capacity. In the case of an accident, no device for emergency operation is required, except for two check valves installed in the RHR pipe and siphon-downflow pipe. In addition, owing to the simplicity of the structure, it is possible to eliminate the potential for equipment malfunctions or human error in the event of an accident.

Finally, an SMR adopting the PX-loop circulation concept does not require any emergency power or related measuring equipment. Therefore, the concept of the PX-loop is suitable for the future ultimate passive operation of the nuclear power plant.



(a) Thermosiphons classification



(b) Applicable thermosiphons circuits

Figure 1. Classification of thermosiphons according to heat-exchange circuits

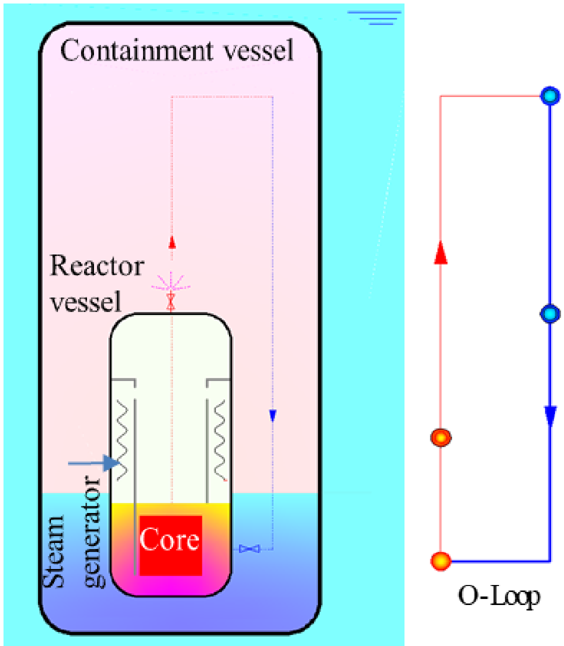
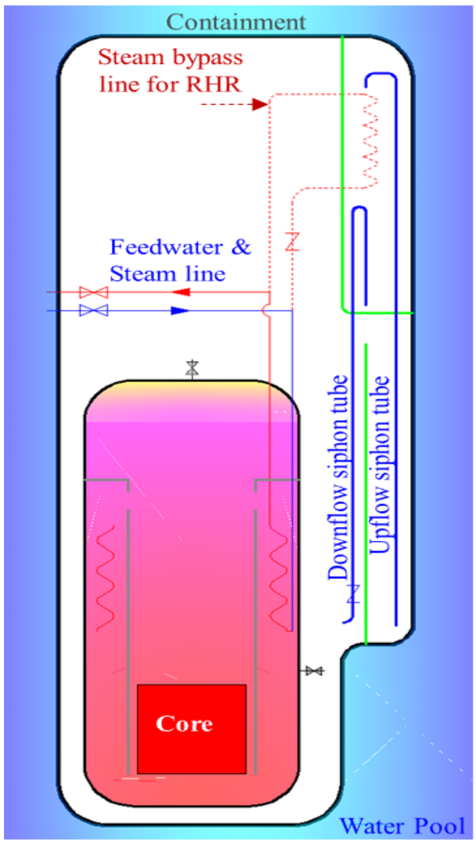
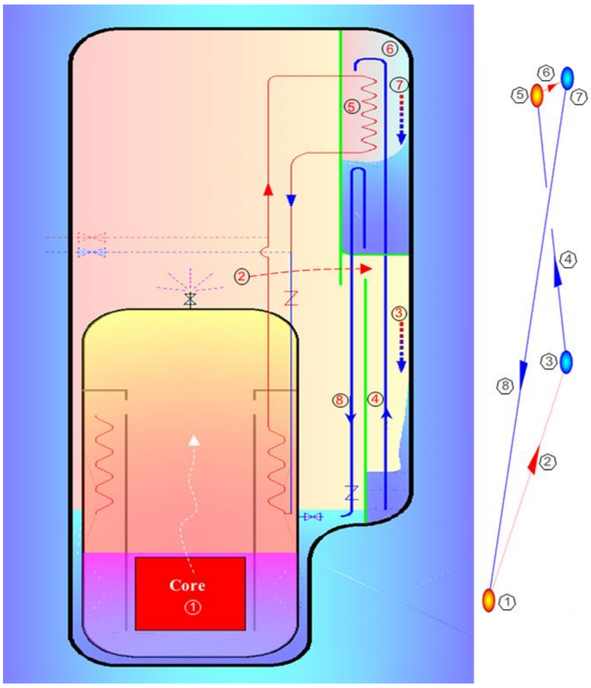


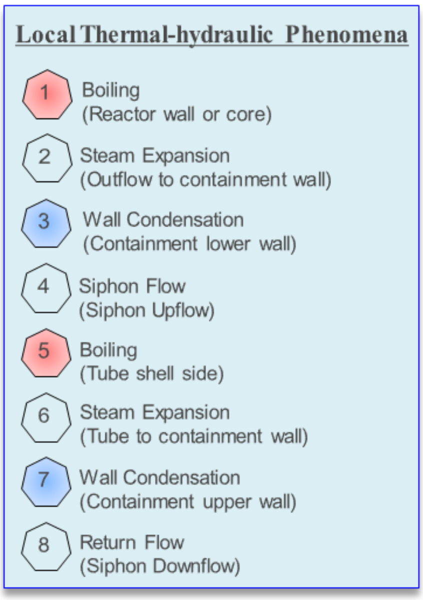
Figure 2. Schematic of O-loop containment structure



(a) Schematic of containment structure of PX-loop



(b) Flow pattern during accident



(c) Local thermohydraulic phenomena

Figure 3. Containment structures of PX-loop and local thermohydraulic phenomena during accident

3. Conclusions

A heat transfer concept, termed a multi-step thermosiphon, was introduced in this study. The multi-step thermosiphon has superior heat transfer capability compared to the existing single-step thermosiphon. To verify this concept, calculations were performed using a two-step thermosiphon with simple and realistic models.

The calculation results were sufficiently consistent to confirm this concept. In particular, among two-step thermosiphons, point-symmetric X-loops have approximately four times greater heat transfer performance than conventional methods, but practical applications may be limited owing to the pulsating flow. On the other hand, it was also confirmed that the PX concept almost maintains high heat transfer performance while eliminating the oscillation flow.

The PX concept presented in this study has several advantages when applied to the containment vessel of an SMR design. This is because its maximum heat transfer rate is theoretically two to four times higher than that of the existing O-loop concept. Consequently, the containment design pressure and volume is significantly reduced.

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