Application of Multi-step Thermosiphon for the Containment Cooling of a Small Modular Reactor

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1. Introduction

The new concept of a multi-step thermosiphon is a heat exchange method that performs heat transfer by natural circulation accompanied by multiple phase change in a closed loop. 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.

In this study, a two-step thermosiphon, which is practically applicable among multi-step thermosiphons, is investigated. The proposed configuration exhibits a superior heat transfer rate compared to a conventional single-step thermosiphon. Furthermore, a modified asymmetric two-step thermosiphon, termed PX, is proposed as a passive infinite cooling concept [1, 2]. The PX concept can be effectively applied to containment cooling in small modular reactors (SMRs).

2. Concept of multistep thermosiphon

The circuit models were applied to compare the heat transfer mechanisms of single-step and multi-step thermosiphons. Figure 1 illustrates two discretized heat transfer models used to analyze thermohydraulic phenomena in a continuous heat structure. The heating region is located on the left side, and the cooling region is located on the right side. It was assumed that the total height, width, area A, and flow resistance *f* were the same for both models and that the width compared to the height was negligibly small. Here, the thermal properties *x*, *v*, *p*, *ρ*, *Q*, $\dot{m}$ and *h* are the steam quality, velocity, pressure, density, heat transfer rate, mass flow, and enthalpy, respectively, and *Δy* is the height of each segment of the single-step thermosiphon or local channel of the multi-step thermosiphon. For convenience, the subscripts *O* and *X* represent the type of cycle, single-step and multi-step thermosiphons, respectively, and *fg* is the property difference between the liquid and vapor. Superscripts *1*, *2*, and *i* denote the sequential number of segments or channels in each loop. In each model, it was assumed that both the liquid and vapor were at the saturation temperature.

Hereafter, the single-step thermosiphon is denoted as the O-loop, and the two-step thermosiphon is denoted as the X-loop for simplification of the terms. In the O-loop, the bottom part was assumed to be a saturated liquid 0.0 with a void fraction. The void fraction increased in the heating section by boiling, and the vapor condensed in the cooling section. Thereafter, the void fraction theoretically decreased back to 0.0. In the multi-step X-loop, vaporizing and condensing behaviors occurred repeatedly in each channel.

In the simplified theory of the gravity-dominant two-phase thermosiphon, the momentum balance in the natural circulation loop is $f\rho v^2/2 = \oint \Delta p$. Here, the circular integral of the pressure change for the O-loop is expressed by Equation (1), and the mass-flow rate is expressed by Equation (2). Here $\Delta y = \Delta y^n$ is assumed for all *n*.

$$\oint \Delta p_O = g[(\rho_O^0 + \rho_O^1 + \dots \rho_O^{n-1}) - (\rho_O^1 + \rho_O^2 + \cdots \rho_O^n)]\Delta y \tag{1}$$

$$\dot{m}_O = \left(\frac{2\bar{\rho}A^2}{f} g(\rho_O^0 - \rho_O^n)\Delta y\right)_O^{1/2} \tag{2}$$

In addition, the circular integral of the pressure changes in the multi-step X-loop is given by Equation (3), and the mass flow rate is expressed as Equation (4).

$$\oint \Delta p_X = g[(\rho_X^0 - \rho_X^1) + (\rho_X^0 - \rho_X^1) + \cdots (\rho_X^0 - \rho_X^1)]\Delta y \tag{3}$$

$$\dot{m}_X = \left(\frac{2\bar{\rho}A^2}{f} ng(\rho_X^0 - \rho_X^1)\Delta y\right)_X^{1/2} \tag{4}$$

Assuming a fully evaporating-condensing process and the same pressure condition, each density of the top region is given by $\rho_O^n = \rho_X^1$. In addition, if the ratio of the loop-averaged density $\bar{\rho}_X/\bar{\rho}_O \approx n$, because the single-phase liquid region of the X-loop is approximately *n* times longer than that of the O-loop, the ratio of the mass flow rate for the O- and X-loops becomes Equation (5) using Equations (2) and (4). This implies that the mass flow rate in the X-loop becomes n times higher than that in the O-loop at the limiting case. If the length of the horizontal parts of each loop are relatively negligibly small compared to the height of vertical parts, the total length and shape of each loop are almost equal at the limiting case.

$$\frac{\dot{m}_X}{\dot{m}_O} \approx n \tag{5}$$

Similarly, the heat transfer rate in the heating or cooling section is expressed as $Q = \dot{m}\Delta h$[3], The total heat transfer rates in the O- and X-loops are given by Equations (6) and (7), respectively. Here, Δx^i is the i-th step increase of vapor quality.

$$\sum Q_O^i = \dot{m}_O\left[\Delta x_O^1 h_{fg,O} + \Delta x_O^2 h_{fg,O} + \cdots \Delta x_O^n h_{fg,O}\right] \tag{6}$$

$$\sum Q_X^i = \dot{m}_X\left[\Delta x_X^1 h_{fg,X} + \Delta x_X^2 h_{fg,X} + \cdots \Delta x_X^n h_{fg,X}\right] \tag{7}$$

Considering the same pressure for each loop, the ratio of total heat transfer rate for the O- and X-loops become Equation (8). The total heat transfer rate indicates that the total heating rate is always the same as the total cooling rate for each loop. The summation of the vapor quality in the O- and X-loops is $\sum \Delta x_O^i = 1$ and $\sum \Delta x_X^i = n$. This implies that the maximum heat transfer rate of the multistep X-circulation loop is n^2 times greater than that of the O-loop. If n =1, it has the same loop configuration and exhibits the same heat transfer rate.

$$\frac{\sum Q_X^i}{\sum Q_O^i} = \frac{\dot{m}_X}{\dot{m}_O} n \approx n^2 \tag{8}$$

3. The application of multi-step thermosiphon for the containment cooling of SMR

Based on the theoretical results, the heat exchange capacity of the X-loop is four times greater than that of the O-loop when n = 2 as shown in Figure 2. Therefore, the proposed concept is particularly suitable for application to SMR containment systems[4]. In an SMR, a containment vessel is installed to isolate the reactor during accident conditions. The containment vessel not only protects the reactor from external hazards but also removes residual heat from the reactor core after shutdown. Thus, it plays a crucial role in both safety and structural integrity.

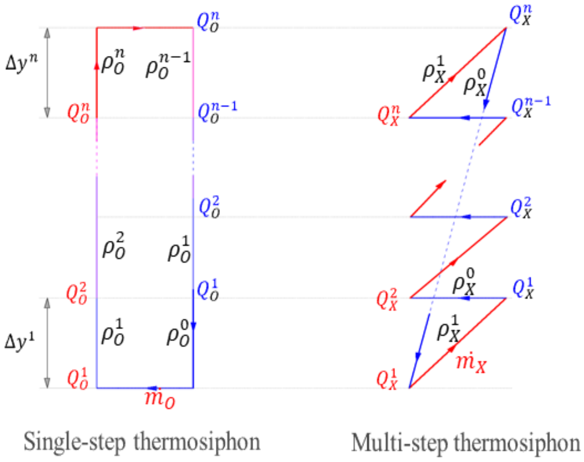
The types of containment vessels may have a structure that utilizes the O-loop concept or the PX-loop concept of modified two-step thermosiphon – the second heat source in X-loop in Figure 2 was moved top part of the loop - as shown in Figure 3(a). In both circulation concepts, steam is condensed on the inner wall of the containment vessel, and the condensed water subsequently flows into the reactor vessel. Subsequently, the water is converted to steam by heating at the core and eventually discharged through the upper valve of the reactor vessel. Although the fundamental heat transfer mechanism is similar in both concepts, the O- and PX-loops differ significantly in the mechanism by which discharged steam is cooled along the containment wall.

Figure 3(a) shows the overall behavior in which the reactor was shut down after the accident, and then the residual heat of the core was discharged to the external pool through the residual-heat removal (RHR) pipe. Figure 3(b) shows the local thermohydraulic phenomena in this case. Figure 3(c) is showing the three-dimensional animation result of hydraulic calculation for the typical SMR in case of small break accident.

To verify this circulation phenomenon, a preliminary analysis was performed [5, 6] 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.

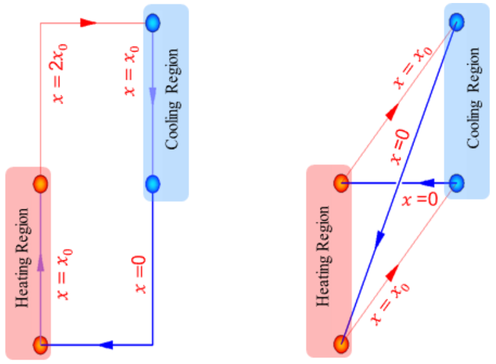
First, it can have the smallest containment volume per reactor power owing to its excellent heat-exchange capacity. In the case of an accident, no device for emergency operation is required, except for two check valves installed in the RHR pipe and siphon-downflow pipe. In addition, owing to the simplicity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



Single-step thermosiphon Multi-step thermosiphon

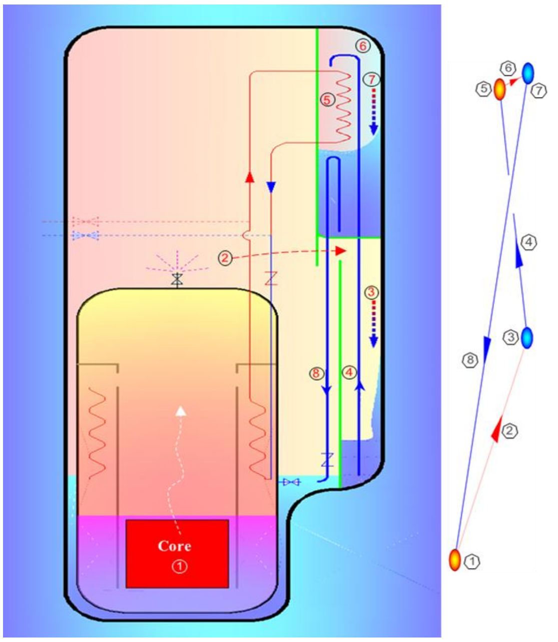
Figure 1. Schematics of discretized models for the natural circulation circuit



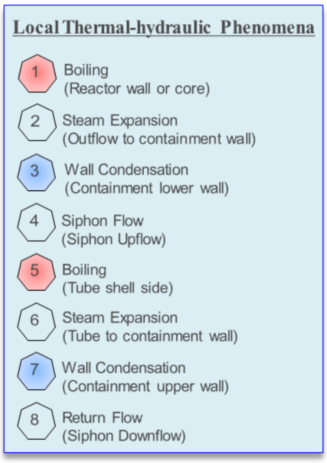
O-Loop : Single step thermosiphon

X-Loop : Two-step thermosiphon

Figure 2. Steam quality distributions of the O- and X-loops when n =2



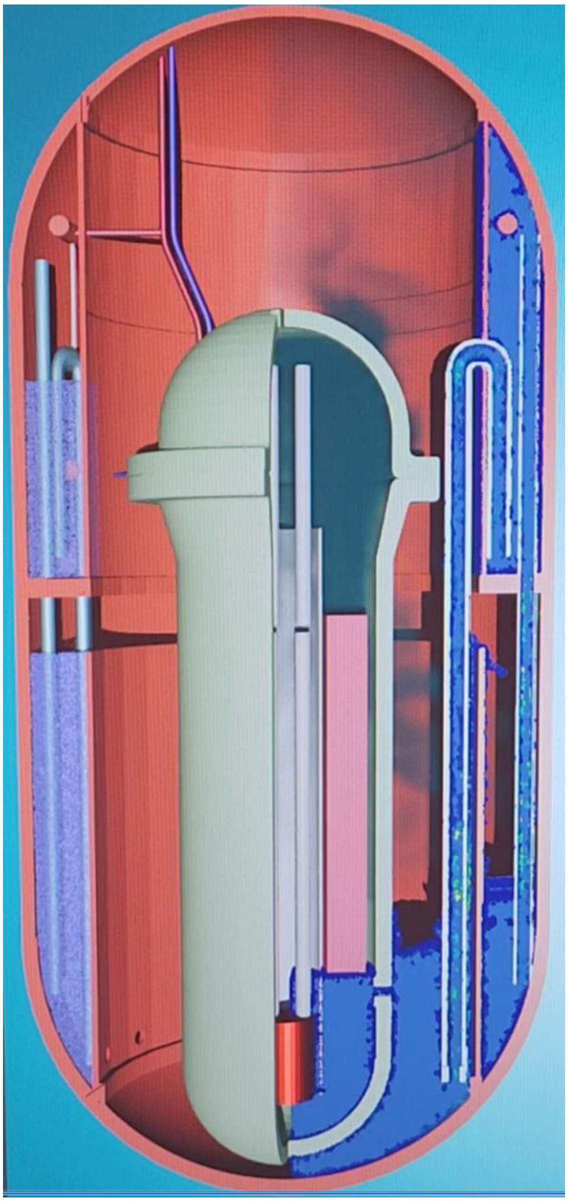
(a) Flow pattern during accident



Local Thermal-hydraulic Phenomena

1 Boiling (Reactor wall or core)
2 Steam Expansion (Outflow to containment wall)
3 Wall Condensation (Containment lower wall)
4 Siphon Flow (Siphon Upflow)
5 Boiling (Tube shell side)
6 Steam Expansion (Tube to containment wall)
7 Wall Condensation (Containment upper wall)
8 Return Flow (Siphon Downflow)

(b) Local thermohydraulic phenomena



(c) Three-dimensional view of hydraulic calculation result in case of small break accident in typical SMR

Figure 3. Local thermohydraulic phenomena of PX-loop and hydraulic calculation result

3. Conclusions

A multi-step thermosiphon concept has been introduced and theoretically analyzed. The results demonstrate that the multistep configuration provides superior heat transfer capability compared to the conventional single-step thermosiphon.

In the case of a two-step thermosiphon (n = 2), the point-symmetric X-loop achieves approximately four times greater heat transfer performance than the conventional O-loop, although practical implementation may be limited by pulsating flow behavior.

The PX that is modified asymmetric two-step thermosiphon concept, presented in this study offers significant advantages when applied to the design of SMR containment. Its maximum heat transfer rate is theoretically about 2 times greater than that of the conventional single-step concept. Consequently, the design pressure and volume SMR containment can be substantially reduced.

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