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Passive Infinite Cooling based on Two-step Thermosiphon

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1. Introduction

The concept of passive infinite cooling (PX) [1] has been developed for Small Modular Reactor (SMR) containment vessel. The PX concept is one of the most important design features that can assure the inherent safety and passive operation of a nuclear power plant without severe accident. The containment vessel with PX cooling function makes the system be safer, simpler and smaller. The two-step thermosiphon phenomena is a key feature of this concept and is newly introduced in the thermal-hydraulics. Recently, newly developed SMR design concepts of mPower, NuScale, and SMART [2, 3, 4] have aimed to enhance both inherent safety and economic competitiveness. However, it is not easy to resolve both contradictory needs at the same time. Most SMRs have the additional power, sensing system and operation procedure for an emergency. In addition to these, operator decision is still needed when the unexpected accidents occur. These could be exposed to other unexpected human errors and accidents. To find a successful path toward solving these problems, it is necessary to simplify the system and unify the diverse functions. Therefore, a newly developed PX concept is introduced to satisfy ultimate safety requirements of future advanced SMR.

2. The concept of multi-step thermosiphon

Two-phase natural convection is a heat transfer mechanism that accompanies fluid circulation and phase change, and its roles are classified according to the internal flow mechanism, as shown in Figure 1. First of all, thermosiphon is classified into two mechanisms of non-gravity and gravity driven thermosiphon. The former is a heat transfer method in microtubules, where the effect of gravity (*g*) is less than that of surface tension (σ), and the latter is natural circulation, where the effect of gravity is dominant over surface tension. And the non-gravity driven thermosiphon is classified into a general heat pipe [5] consisting of a single channel and a pulsating heat pipe [6] consisting of a multi-channel. Here, in the pulsating heat pipe, flow vibration occurs in the front and back of the flow direction, but it is a well-known and good heat transfer mechanism with improved efficiency over a single heat pipe. In the gravity driven thermosiphon, it is divided into the single-step thermosiphon in the single channel, which is widely used up to now, and the multi-step thermosiphon in the multi-channel. The concept of multi-step thermosiphon heat transfer in the multi-channel has been introduced for the first time in the field of heat transfer through this study, and this is based on the basic physical theory of passive infinite cooling concepts used for the cooling of SMR containment vessel. In this study, a two-step thermosiphon, which is highly applicable in the field of industry among multi-channel mechanisms, was studied. The difference between two mechanisms is sequentially repeatability of the boiling and condensation. That is, in single-step thermosiphon, boiling and condensation occur once each in one circulation, whereas in two-step thermosiphon, boiling and condensation occur sequentially twice in one circulation. Similar to the heat pipe concept, the multi-channel method has better heat transfer performance than the single channel method in the heat pipe category. Therefore, in this study, PX having the two step thermosiphon mechanism was applied for the design of SMR containment vessel.

3. Application of two-step thermosiphon

The two-step thermosiphon presented in Chapter 2 was used as the basis of the PX cooling concept. If it is applied to the design of the SMR containment vessel, the thickness of the vessel can be reduced and the cooling capacity can be improved. Figure 2 shows the containment concept of SMR to which the PX concept is applied. The reactor represented in the figure has an overpressure prevention valve installed at the top and a coolant circulation valve installed at the lower side, and both valves are open for natural circulation in the event of an accident. Figure 2 (a) shows the normal operation status of the SMR that produces electricity by generating steam, and Figure 2 (b) shows the heat transfer mechanism after the reactor trip following an accident. It includes the heat release from containment to water pool and same time the heat removal by the Residual Heat Removal (RHR) system. The schematic behavior of heat release to the external water pool are described in detail in the reference [7].

The containment vessel with PX concept is conceptually different from the existing containment vessels currently being developed worldwide. First, it has excellent heat removal performance, so it can maintain a small volume of containment vessel per unit power of the reactor. And it is suitable for the ultimate passive operation that does not require any operation after isolating the feedwater and main steam lines connected to steam generator after reactor trip.

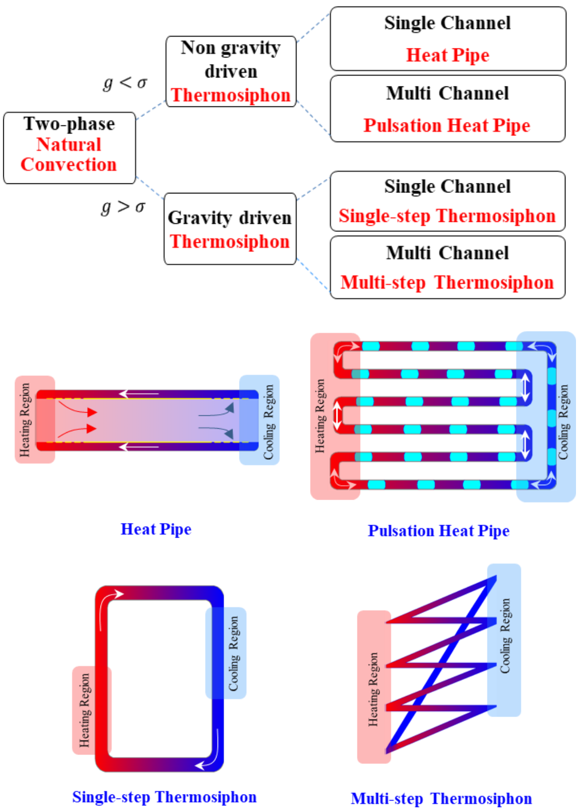
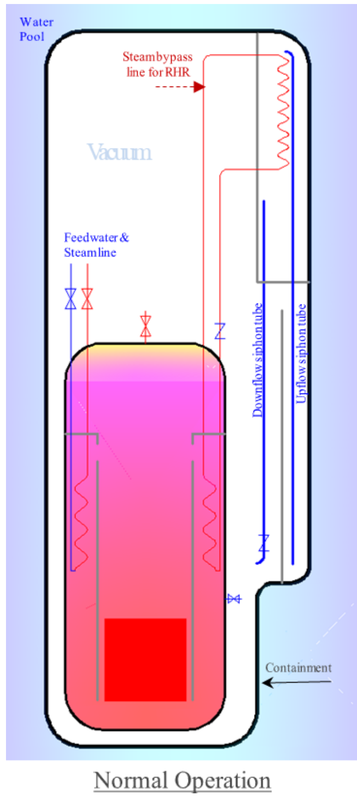


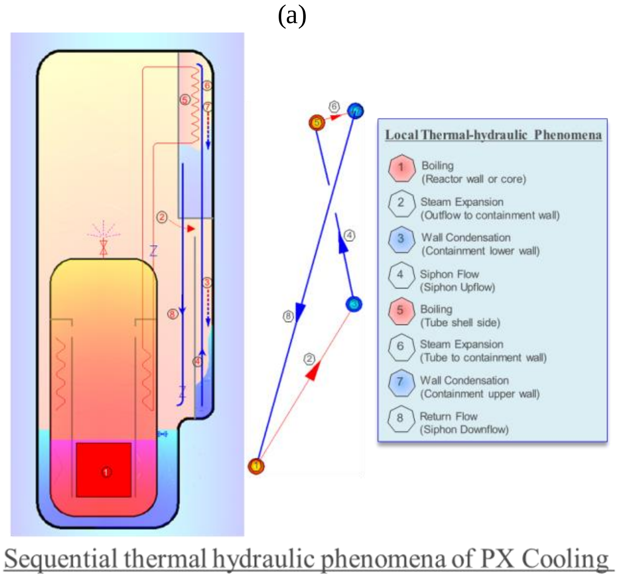
Figure 1. Classification of thermosiphon according to heat transfer mechanism

4. Conclusion

The new PX cooling concept based on two-step thermosiphon presented in this paper has a number of advantages when applied to SMR containment vessel design because it has theoretically superior heat transfer performance than the existing circulation method based on the concept of single-step thermosiphon. By simultaneously removing heat from the reactor core and steam generator after the reactor trip, the mass release from the reactor can be effectively reduced. And the stored energy of the containment vessel is rapidly transferred to the external water pool using the PX cooling method, so the containment vessel design pressure can be lowered and the containment volume can be reduced. In addition, the SMR adopting PX cooling concept does not require any operator action other than isolating the feedwater and main steam line after reactor trip following an accident, so it can passively cool down the residual heat from the core for a long time. Therefore, there is no need for an emergency related power supply or instrumentation system and cables. From a structural point of view, it is a new SMR containment concept that can satisfy both enhanced safety and economic competitiveness due to its simple structure. Furthermore, in this design there is no pipe passing through the vessel because RHR system is installed inside the containment vessel.



(a)



(b)

Figure 2. The concept of SMR containment vessel with PX cooling (two-step thermosiphon)

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