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Simple analysis of an External Vessel Cooling Thermosyphon for a Sodium-cooled Fast Reactor

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1. Introduction

Up to date, many systems for the decay heat removal (DHR) of sodium-cooled fast reactor (SFR) were introduced so far. Mainly, two major branches of DHR concept was designed and developed; one is direct decay heat removal through sodium pool or auxiliary loop and the other is indirect cooling through reactor vessel wall.

Direct decay heat removal method was utilized on KALIMER (Korea Advanced Liquid MEtal Reactor) [2], which is an SFR developed by KAERI (Korea Atomic Energy Research Institute). KALIMER has three different DHR systems: two non-safety grade systems and one safety grade system. The non-safety grade systems are an IRACS (Intermediate Reactor Auxiliary Cooling System) and a steam/feedwater system. The safety grade system is a PDRC (Passive Decay Heat Removal Circuit) [2][3]. In case of the foreign reactor designs, ABTR (Advanced Burner Test Reactor) has a DRACS (Direct Reactor Auxiliary Cooling System) [6], a PFBR (Indian Prototype Fast Breeder Reactor) has an SGDHRS (Safety Grade Decay Heat Removal System) [7], and an EFR (European Fast Reactor) has DRC (Direct Reactor Cooling) [8][9]. Those designs have advantage on relatively high decay heat removal capacity. However, larger vessel size due to subsidiary in-vessel structure and possible accident propagation to reactor induced by sodium fire.

On the other hand, indirect vessel cooling method was introduced on PRISM safety system design. PRISM (Power Reactor Inherently Safe Module) has a different type of DHR system called a RVACS (Reactor Vessel Auxiliary Cooling System) [5] that utilizes natural convection of air to remove decay heat from the reactor vessel wall in the reactor cavity. The RVACS design has no in-vessel structures so that it can minimize the vessel size and complexity. Nevertheless, vessel cooling method has relatively low DHR performance because it relies on the natural convection of air and radiation heat transfer from reactor vessel wall, which were inefficient in the view point of thermal design.

This paper was studied to propose a conceptual design of a passive DHR system that alleviates the disadvantages of both decay heat removal method. As a background conditions, only for a SFR, especially for iSFR (Innovative Sodium-cooled Fast Reactor) [10][11], was considered as a reference reactor. The iSFR is a 150MWe scale pool-type SFR developed by KAIST (Korea Advanced Institute of Science and Technology). The design was inspired by the PGSFR (Prototype Gen-IV Sodium-cooled Fast Reactor) developed by KAERI, but has unique features, include extended core lifetime [10], increased thermal efficiency from using the S-CO2 Brayton cycle [11] and improved safety features. In the paper, we studied about the external vessel cooling by two phase closed thermosyphon. Thermosyphon attached on the surface of containment (guard) vessel dumped heat from vessel wall to ultimate heat sink. The system design was proposed by conducting simple analysis and checks the improvements beyond the disadvantages of current DHR system for SFR mentioned above.

2. Design Method

2.1 Design Objectives

Three objectives were considered to design the proposed passive decay heat removal system. First, the decay heat removal capacity should be increased compared to conventional RVACS. The DHR requirement was set to be 1% of nominal thermal power with 10% of uncertainty, which is the amount of heat generated from reactor core 3 hours after shutdown. Moreover, failure of four out of two thermosyphon modules was considered. In total, 8.64MW of decay heat was design to be removed by normal operation of four thermosyhpon modules.

Next objective is the elimination of sodium fire occurred by decay heat removal system itself. By using indirect external vessel cooling method, the accident propagation through the proposed system was totally shut off. Also, inactive working fluid was selected to eliminate all kind of possible chemical reaction, including sodium fire, sodium-working fluid, and working fluid-air/water reaction.

The other requirement is the simplicity of the design. To reduce the complexity of design, external vessel cooling was utilized to remove in-vessel structure and the size of overall system was optimized by the analysis. The layout of the system is presented on Fig. 1.

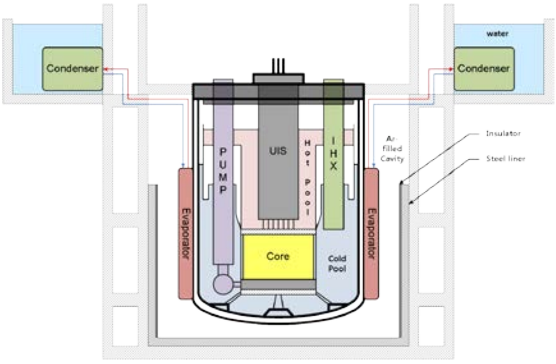

Fig. 1: Schematic diagram of ex-vessel thermosyphon

2.2 Selection of the Working Fluid and Structure Material

In order to select adequate working fluid, two aspects were considered: thermodynamic properties and chemical stability. Under the temperature range of SFR application, four widely-used candidates of working fluid were reasonably available: Dowtherm, mercury, cesium and potassium. Their thermodynamic properties were shown and Table I. According to Table I, metallic fluid shows much better property than organic fluid, in here Dowtherm.

Table I: Thermodynamic properties of working fluid candidateds for their saturation temperature

	k_l [W/mK]	ν_l [m^2/s]	h_{lv} [kJ/kg]	$h_{lv}\times\rho_l$ [MJ/m^3]
Dowtherm	0.101	3.17×10^{-7}	296.57	252.65
Mercury	12.15	0.675×10^{-7}	294.89	375.60
Cesium	17.06	1.10×10^{-7}	490.90	721.62
Potassium	30.32	2.21×10^{-7}	1925.4	1277.9

In consideration of their chemical stability, cesium and potassium are unavailable due to their violent reaction with water and air. On the other hand, mercury has no reaction with water, air and sodium. Therefore, proper working fluid was selected as mercury. The chemical reactivity with the working fluid, the thermal resistance under high temperatures, the corrosion resistance against the working fluid and the operation margin were considered for each material. Based on all of these factors, stainless steel (SUS 316) was selected as the structural material when using mercury as the working fluid.

2.5 Thermosyphon Design Process

After determining the maximum allowable cold pool temperature, thermal design was conducted to determine the design parameters for the thermosyphon. This analysis was also conducted by MATLAB R2014a with in-house code, similar to the previous step. Based on Cunha and Mantelli`s [12] process, a modified version of thermal design process was used for the analysis. The modified design process is shown in Fig. 2.

The overall process started with condenser analysis. First, we calculated the condenser wall temperature, and then we assumed, at proper mercury temperature, that the heat transferred by condensation of mercury satisfied the required amount of heat removal. After the saturation temperature of mercury was determined, the iteration was repeated with assumed evaporator wall temperatures until heat transferred into the mercury pool and film by boiling was equal to the required decay heat removal. As such, the thermosyphon removed sufficient decay heat during steady state. Then, we calculated the temperature of vessel structure for the containment vessel, reactor gap and reactor vessel to estimate the average cold pool temperature. The process was repeated to determine the optimal design parameters within conditions that do not violate the design criteria, including the maximum allowable cold pool temperature, the mercury working temperature (250~650 ℃) and the evaporator height (<10.0 m).

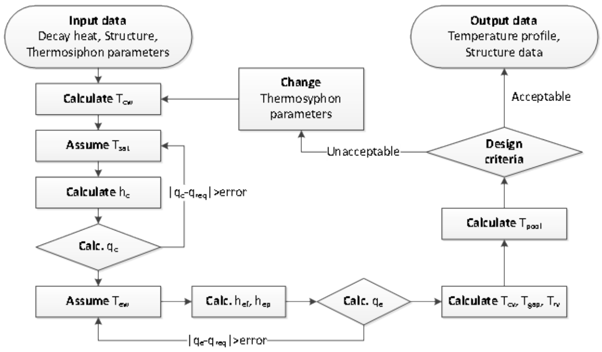

Fig. 2: Flow chart of design analysis

3. Result and discussion

The overall design parameters of the thermosyphon are summarized in Table II The evaporator length, condenser tubes and mercury filling ratio were optimized based on this analysis. Other parameters were adjusted to be adequate in the iSFR design. The equilibrium temperature of the cold pool did not violate the design criteria, and the temperature inside the vessel also satisfied design constraints. The proposed design showed better performance than a conventional RVACS, which is shown in Fig. 3. The proposed ex-vessel thermosyphon showed better performance, approximately 3 times better, than DHR capacity over the temperature range for the containment vessel. Fig. 3 also shows that the maximum DHR capacity of the ex-vessel thermosyphon was estimated to be 11.8 MW.

Table II: Design parameters of thermosyphon

Thermosyphon Module	
Number of modules	4
Mass of mercury	9000 kg / module
Filling ratio	32.67%
DHR performance	2.16 MW/ module
Material	SUS 316
Evaporator (Hollow shell)	
Length	10.0 m
Wall thick	10 mm
Envelope thickness	30 mm
Vessel coverage	100% (radial) 63% (axial)
Surface area	71.66 m^2
Adiabatic Section (Single tube)	
Length	4.0 m
Diameter	0.2 m
Condenser (Multiple tubes)	
Length	1.5 m
Number of tubes	7
Inner diameter	40 mm
Outer diameter	44 mm
Surface area	1.58 m^2

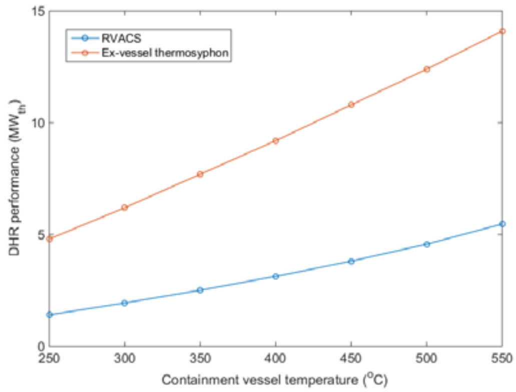

Fig. 3. Comparison of DHR performance

4. Conclusions

In this paper, an ex-vessel thermosyphon design was proposed for the removal of decay heat for an iSFR. The proposed ex-vessel thermosyphon was designed to remove decay heat in both transient cases and BDBA cases, such as vessel failure. Proper working fluid was selected based on thermodynamic properties and chemical stability. Mercury was chosen as the working fluid, and SUS 314 was used for the corresponding structure material. Possible chemical reactions and adverse effects from using the thermosyphon were inherently eliminated by the system layout. A model for a high-temperature thermosyphon and numerical algorithms were used for the analysis.

As a result of the simulation, the thermosyphon design was optimized, and it showed sufficient DHR performance to maintain core integrity. Although the ex-vessel thermosyphon uses the same ex-vessel cooling method as an RVACS, the proposed design was approximately 3 times better than the conventional RVACS design. Therefore, the proposed ex-vessel thermosyphon could also be utilized for reactors with higher power, to which a conventional RVACS cannot be applied.

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