Numerical Analysis of In-Vessel Retention using MARS-Ga for APR1400 under the Ga-based External Reactor Vessel Cooling

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1. Introduction

IVR-ERVCS (In Vessel Retention External Reactor Vessel Cooling System) is known to be an effective method for maintaining the integrity of the reactor vessel when severe accident occurs in a nuclear power plant [1]. ERVCS must provide sufficient thermal margin of the coolability for reactors. To stabilize and terminate the severe accident through enhancing the coolability of the degraded core, this paper introduces an approach to avoid heat removal limit by replacing flooding material from the borated water to the liquid metal, gallium. The attractive properties such as the low melting point, high boiling point, and no reaction with water ensure that gallium can play an important role in nuclear safety as an alternative coolant in the gap between the vessel and the vessel insulation. The properties of liquid gallium compared to other materials are indicated in Table 1 and 2 [2,3,4,5,6]. For the investigation on the effect of gallium for IVR-ERVCS, numerical simulation for severe accident in APR 1400 using MARS-LMR was performed.

Table I: Thermo physical properties of liquid metals

	Na	LBE	Ga
Atomic Weight	22.997	208	69.723
T_m (°C)	97.8	123.5	29.76
T_b (°C)	892	1670	2204
ρ (kg/m^3)	*880	*10300	6095
C_p (J/kg·K)	*1300	*146	381.5
k (W/m·K)	*76	*11	29
μ (10^{-3}kg/m·s)	*0.34	*1.7	1.810
Σ_a (m^{-1})	0.03147	0.003034	0.148
β (10^{-6}K^{-1})	200	130	59.5

* evaluated at 300°C
Thermo properties of gallium are evaluated at 32°C

Table II: Relevant physical properties of liquid gallium

	Gallium
ρ (kg/m^3)	6330-0.7717T
μ (kg/m·s)	$0.01207\text{-}50754\times10^{-5}T+7.891\times10^{-5}T^2$
β (K^{-1})	0.7717/ ρ
k (W/m·K)	-7.448 + 001256T

2. Methods and results

2.1. Gallium-based IVR-ERVCS

There are several advantages by using gallium-based IVR-ERVCS such as avoiding the heat removal limit of CHF during boiling of water and reducing the probability of the steam explosion caused by molten core material released from a reactor vessel. In this sense, gallium can work properly as one of the methods determining the ERVC in the nuclear power plant. Fig. 1 shows that two fluids were separated by the block structure [7]. This configuration indicates that sufficient gallium injection and heat transfer area between the liquid metal and the borated water must be determined to success of the ERVC.

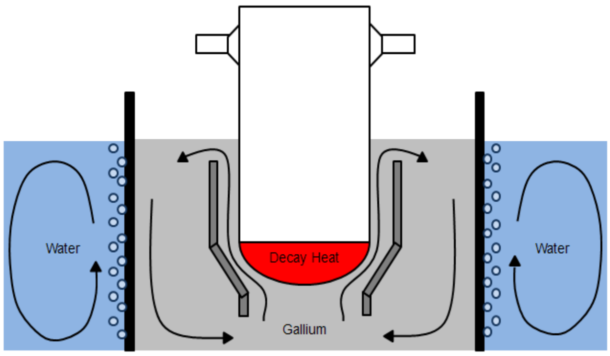

Fig. 1. Configuration with gallium and borated water [7]

2.2. MARS-LMR modeling for IVR-ERVCS

MARS-LMR for liquid metals uses the soft sphere model based on Monte Carlo calculations for particles interacting with pair potentials [8]. Although MARS was originally intended for a safety analysis of light water reactor [9], gallium properties were newly added to this code which is applicable for the thermal hydraulic systems of liquid gallium can be simulated for numerical and parametric studies. Fig. 2 shows the MARS-Ga nodalization around reactor vessel and the cavity for the simulation of the APR 1400 as well as the barrier between gallium and borated water. The gallium flow area was divided into two regions between reactor vessel and insulator as well as insulator and barrier. The heat flux distribution in the lower plenum of the APR 1400 is one of the cases calculated from MAAP analysis of KAERI [10].

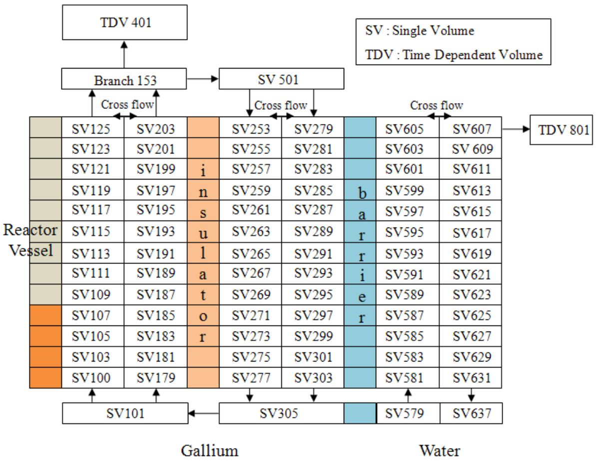

Fig. 2. Nodalization of gallium-based IVR-ERVCS

2.3. Results

The capacity of water pool as ultimate heat sink was assumed temporarily. Fig. 3 and 4 indicate the temperature distribution of outer vessel wall and liquid gallium respectively.

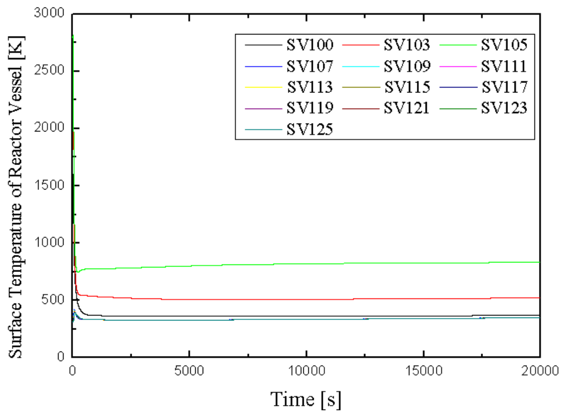

Fig. 3. Surface temperature distribution of reactor vessel

The analysis was primarily focused to examine the range of temperature for outer reactor vessel wall and liquid gallium. As shown in Fig. 3 and 4, the maximum temperature of outer vessel wall and liquid gallium are 560°C and 100°C respectively. It is found that the maximum temperature in the gallium region is below the boiling point of gallium. Also, the natural circulation flow was formed ~1030kg/s in the gallium region near the reactor vessel. These results show that gallium-based IVR-ERVCS has the possibility to apply nuclear power plant as the CFD analysis [7].

3. Conclusion

In this study, the numerical analysis of gallium-based IVR-ERVCS using MARS-LMR was performed. The range of temperature distribution in this system was

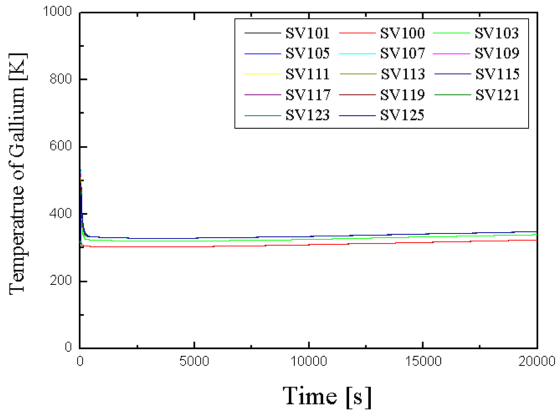

Fig. 4. Temperature distribution of liquid gallium

considered as an important factor and then the possibility of ERVC using liquid gallium was confirmed. In addition, It will perform the sensitivity studies for the heat transfer area between liquid galium and borated water to design the optimum ERVC using liquid gallium.

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