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Visual study of heat removal characteristics for IVR-ERVC cooling system using oil flooding concept

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1. Introduction

After the Fukushima nuclear accident occurred [1], many researchers assumed that the reactor vessel of Fukushima plant would be damaged. Through the core damage progression, a significant amount of core material can be degraded and relocated downward into the lower head of the reactor vessel. When the proper cooling system was not adopted at that time, the corium could be discharged from the damaged reactor vessel [2]. The results from Fukushima accidents give lesson that the integrity of the reactor vessel should be protected to minimize the spreading of radioactive materials beyond the boundary. It is called as in-vessel retention (IVR) or in-vessel corium confinement and cooling. One of the effective features for the IVR is an external reactor vessel cooling (ERVC) strategy. The effectiveness of IVR-ERVC has been studied for decades by many researcher [3, 4, 5]. The main heat removal mechanism of IVR-ERVC condition is boiling heat transfer on the outer surface of the vessel. However, the thermal margin of this system is limited by critical heat flux (CHF). When CHF occurs, the heated surface is covered with vapor film. A few of CHF studies have been carried out with test facilities simulating the flow geometry and conditions of IVR-ERVC [6, 7].

Recently, flooding the liquid metal into reactor vessel cavity was proposed conceptually by Park and Bang [8] to enhance the heat transfer limit. Although the heat was ultimately removed by boiling of water coolant in an additional inventory, the integrity of the reactor vessel could be protected by reducing the focusing effect. However, there are some problems to adopt the liquid metal system such as economic efficiency, ablation and corrosion to the reactor vessel. For this reason, it is required to investigate the heat removal characteristics with alternative flooding material. In present study, oil flooding concept was established to evaluate the improved heat transfer without CHF issues.

2. Experimental setup

There is an additional catcher-like structure for IVR-ERVC cooling system using oil flooding concept. In this study, the structure is defined as a hybrid core catcher for ex-vessel core catcher. This structure has a hemispherical shape to completely cover the bottom of reactor vessel. The oil can be injected to flood the cavity space for ERVC.

Figure 1 shows the test section for the experiment. The decay heat was simulated using the cartridge heaters. The cartridge heaters were inserted in the heated object. The material of the heated object was copper which was used to manufacture the desired geometry. 10 kW electric power was applied to this object via cartridge heaters. Table I shows the physical properties of flooding materials. The refrigerant-123 was used as working fluid in order to investigate CHF phenomenon at limited heat flux condition for the current facility capacity. The R-123 has a low boiling point of 27.6 ^{o}C, which was about 8 times lower than a predicted CHF value of water. The melting point of Dowtherm-RP is -33.9 ^{o}C while its boiling point is 353 ^{o}C. The temperature range is wide enough to operate the oil in a liquid phase. The Prandtl number of Dowtherm-RP is about 3.80 times greater than one of R-123.

The experimental apparatus was composed of test section, condensers, power controller, and data acquisition system. The first stage of power is 250W. After the steady-state condition has been reached, a stepwise power escalation was initiated with increments of 250W. Each power step lasted 10 min until a new steady state was achieved. In the test, two candidates were proposed as the flooding conditions, as shown in Figure 2. The bubble behavior for heat removal characteristics of new ERVC was observed on the heated surface, using a high-speed video camera (1000 frames per second).

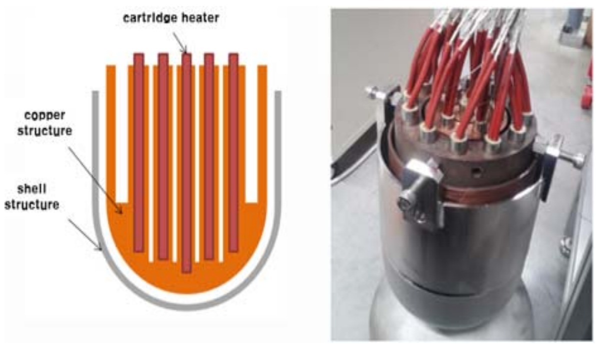
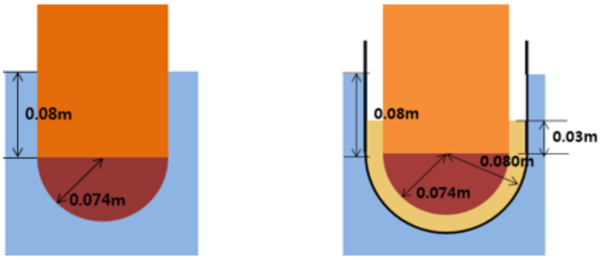


Fig. 1. Test section simulating the reactor vessel.



(a) Case 1 (b) case 2

Fig. 2. Flooding conditions for IVR-ERVC strategy; (a) bare condition, (b) oil flooding condition.

Table I: Physical properties of flooding materials

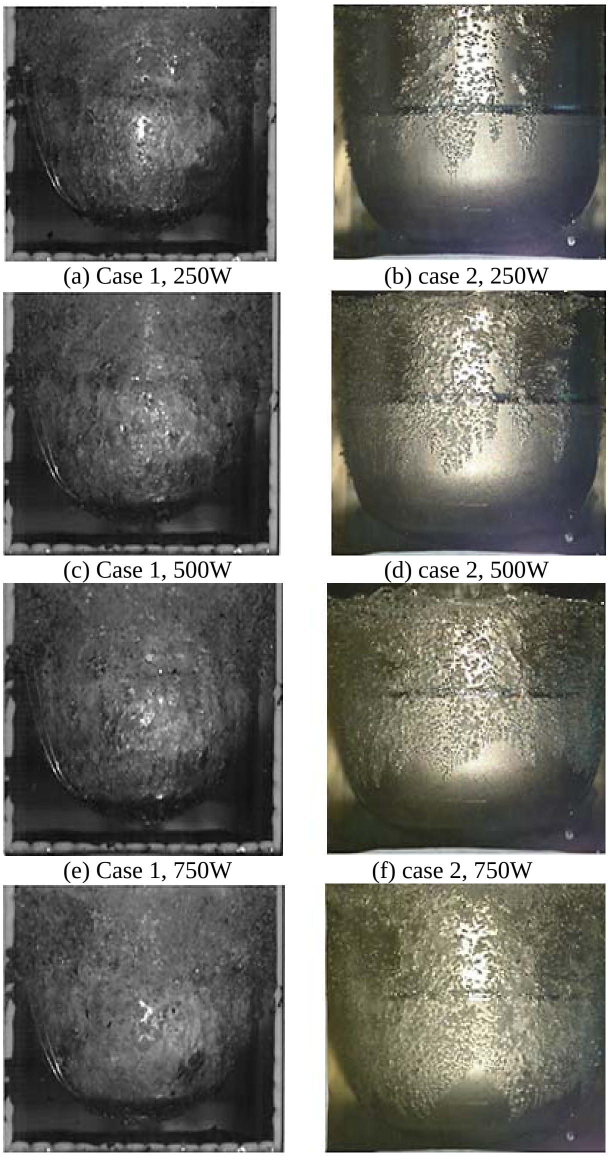
	R-123	Dowtherm-RP
Boiling point (°C)	27.6	353
Density (kg/m^3)	1464	937
Specific heat (kJ/kg/K)	1.03	2.01
Dynamic viscosity (mPa·s)	0.449	1.32
Thermal conductivity (W/m/K)	0.076	0.115
Prandtl number (-)	6.09	23.1

3. Experimental results and discussion

Figure 3 shows the bubble behavior on the heated surface with power and oil flooding condition. The difference between case 1 and case 2 is the effective boiling heat transfer area. The effective boiling heat transfer area would be different depending on the flooding condition. The area of the small hemispheric geometry made of the copper is an effective boiling heat transfer area in case 1. When the oil was flooded, the effective boiling heat transfer area changed. The effective boiling heat transfer area will be an enlarged area of the hemispheric geometry and a portion of the cylindrical geometry on the catcher structure.

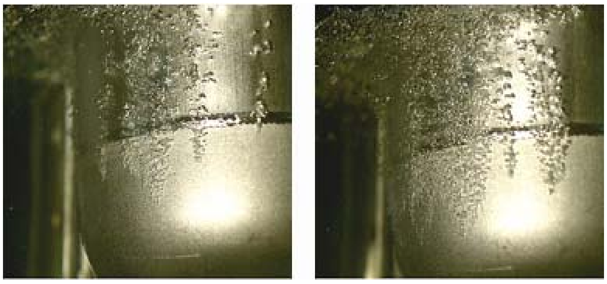
When the oil was flooded as the new IVR-ERVC concept, we can observe different nucleation site on the catcher structure in comparison with that of case 1 at the same power conditions. In case of oil flooding test, the nucleation site was localized on the surface of heated object, as shown in Figure 4. It was driven by natural convection of oil with high Prandtl number. The amount of generated vapor was increased when the high power of the cartridge was applied. The temperature of the surface would also be dropped owing to rapid quenching. The quenching was caused by the developed bubble which was gone away from the heated surface. The single phase heat transfer was in major heat transfer mode on the cooper structure.

The different bubble behavior was observed in the heated surface beyond 1000W at both flooding condition. The small-size bubble merged into larger one along with the heated surface. The formation of larger bubbles or higher void fraction is considered as an indicator of critical heat flux condition causing critical damage on the reactor vessel. The formation of larger bubbles or higher void fraction is considered an indicator of the CHF condition causing critical damage to the reactor vessel. In the oil flooding concept, heat was dissipated more slowly through the oil itself. This physical phenomenon can lead hot spot on the heated object. Even though the enlarged heat transfer area is considered the factor for preventing CHF, heat transfer mode by natural convection can increase thermal load to reactor pressure vessel.



(a) Case 1, 250W (b) case 2, 250W
(c) Case 1, 500W (d) case 2, 500W
(e) Case 1, 750W (f) case 2, 750W
(g) Case 1, 1000W (h) case 2, 1000W

Fig. 3. Bubble behavior on the heated and the catcher surface with power and oil flooding conditions.



(a) Case 2, 250W (b) case 2, 500W

Fig. 4. Localized nucleation site on the catcher surface under oil flooding condition.

4. Conclusions

The present work found that natural circulation by the oil concentrated nucleation site at specific region on the hybrid core catcher structure. The localized nucleation site was induced by the formation of hot spot on the heated surface. There was a different bubble behavior in the heated surface beyond 1000W at both flooding condition. The small-size bubble merged into larger one along with the heated surface. The bubble coalescence or higher void fraction was considered as an indicator of critical heat flux phenomenon causing critical damage on the reactor vessel. In case of the oil flooding condition, the heat transfer area was enlarged up to 1.8 times compared to the original area of the reactor vessel. It can enhance the thermal margin regarding CHF. More quantitative experiments for heat removal characteristics are required to guarantee enough margin of successful IVR-ERVC without CHF issue.

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