Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 26-27, 2017

Passive IVR-ERVC Concept with Existing Solid-liquid Phase Change Material in Insulator

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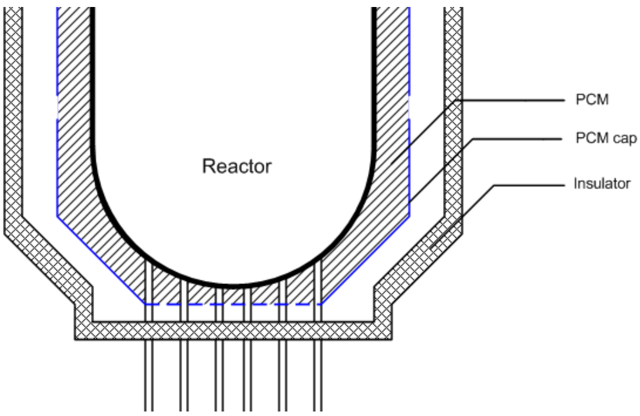
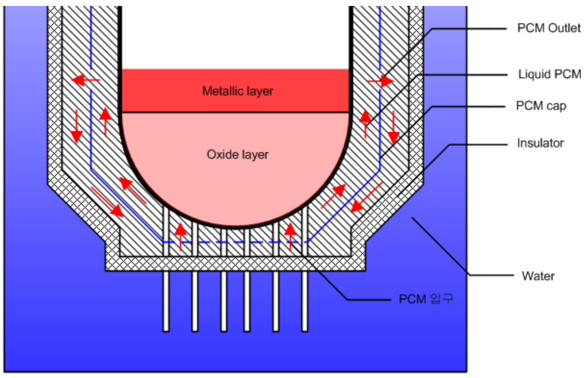
1. Introduction

Due to the problem of the radiation leak from a nuclear fuel, it is important to consider the accident occurred core melt. Therefore, the management of the corium in reactor vessel was a key technology during the severe accident. The IVR-ERVC strategy was applied in various nuclear power plants such as AP600, AP1000, CAP1000, and Loviisa [1]. In APR1400, in-vessel retention by external reactor vessel cooling (IVR-ERVC) is applied [2,3]. The coolant for IVR-ERVC of APR1400 was moved from the In-containment refueling water storage tank by the pumps. The safety margin of the critical heat flux on the reactor vessel was low because of the high reactor power and uncertainty [4]. Therefore, it is essential to get reliability or passivity to improve IVR-ERVC strategy.

In this paper, the two-layer cooling strategy was investigated by using the phase change material (PCM). Fig.1 shows the conceptual design of the IVR-ERVC with PCM. The PCM is located between the reactor vessel and storage cap. It is possible to decrease the heat loss only with radiation heat transfer from the cap to the insulator in steady state condition. In. Fig. 1(b) shows the long-term cooling with water as the ultimate heat sink from IRWST. This two-layer shape was similar to the gallium-water IVR-ERVC [5]. The heat transfer area is expanded and it is possible to get sufficient thermal margin.



(a) Steady state



(b) Long term cooling

Fig. 1 IVR-ERVC concept with PCM

The experimental test was conducted with low melting temperature PCM and refrigerant (R123) in small scaled test facility during heat-up and steady state condition. The results showed the surface temperature of the vessel wall and heat load. The visualization of the two-phase heat transfer was investigated for qualitative heat transfer performance. Results show that the concept of the IVR-ERVC with PCM can be possible to enhance the thermal margin and suggest the new candidate of the IVR-ERVC.

2. Experimental Setup and Procedure

To confirm the thermal performance of the PCM, transient and steady state test were conducted with small scale test facility. The test condition was summarized in Table. I. The heat-up transient means air convection on the outer surface. IE-RP2 to IE-RP4 use the R123 for coolant instead of the water in APR1400.

Table. I Test matrix of the PCM IVR-ERVC

Test number	Coolant	Intermediate material	Heat load and condition
IE-R1	Air	Non	Heat-up transient (500 W)
IE-RP1	Air	PCM(RT31)	
IE-R2	R123	Non	Steady state (250 W)
IE-RP2	R123	PCM(RT31)	
IE-R3	R123	Non	Steady state (500 W)
IE-RP4	R123	PCM(RT31)	

Table. II Phase change material property [6]

Name formula	Melting temperature (ºC)	Density (kg/m^3)	Latent heat (kJ/kg)	Thermal conductivity (W/mK)	Density (kg/m^3) Solid/Liquid
n-nonadecane $C_{19}H_{40}$	30.4	777	182	0.2	890/770

The schematic of the test facility is shown in Fig. 2. To show the effect of the PCM between vessel and insulator, the vessel with 19 cartridge heater and insulator geometry were used during the tests. The air temperature was 21 ºC and the melting temperature of the PCM was 30.4 ºC. The detail properties of the PCM was shown in Table. II.

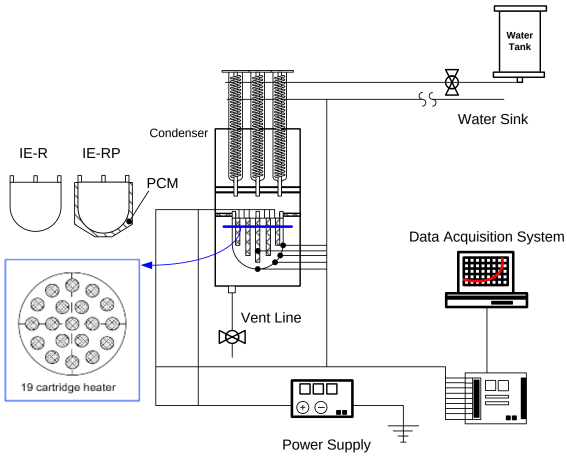


Fig. 2 Schematic of the test facility

3. Results and Discussion

To analyze the effect of the PCM in the insulator of the APR1400, the temperatures of the reactor wall and generated bubbles were investigated according to the heat load.

3.1 Heat-up condition

Although IE-RP1 has an additional layer, the temperature increase of the vessel wall was decreased due to the phase change inside of the insulator-shaped geometry. 400ml of the PCM was inserted to fully cover the heated area. In experimental results, the total heat removal from the latent heat was 56.42 kJ and it showed the difference between IE-R1 and IE-RP1 in Fig. 4. From the Eq. 1, the theoretical heat removal during the heat-up was 59.3 kJ.

$$m_{copper} C_{p,vessel} \Delta T = Q_{removal} \qquad (1)$$

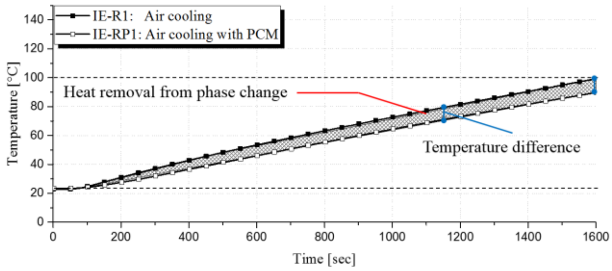
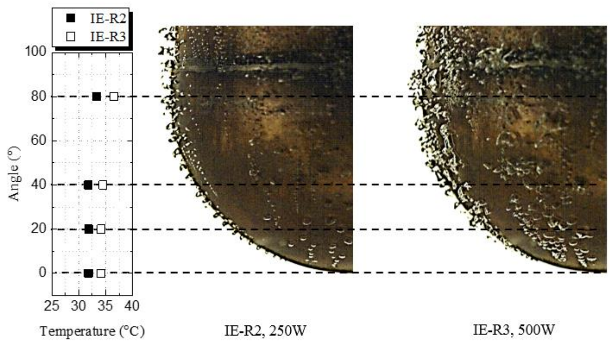


Fig. 4 The surface temperature of the reactor vessel during heat-up transient condition

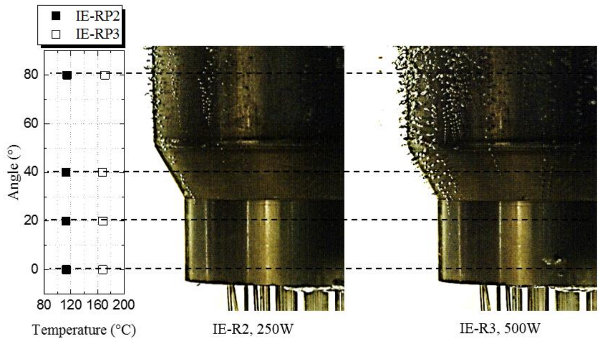
3.2 Steady state condition

The results of the visualization show the generated bubble and its growth on the surface of the vessel. The visualization of the vessel wall and wall temperature according to the angle is shown in Fig. 5. In the case of IE-R2 and IE-R3, the generated bubbles were decreased and vessel wall temperature was highly increased due to PCM layer and insulator-shaped geometry. Due to the low thermal conductivity of PCM, the large difference in temperature between vessel wall and insulator was measured. The wall of the insulator was not measured but it can be predicted from the amount of the bubbles generation. Therefore, it is possible to confirm the decrease of the heat flux.

This strategy has a high temperature of the vessel wall. Therefore, the consideration of the vessel failure was also needed. The suggested candidate of the PCM for applying the IVR-ERVC was high thermal conductivity PCM such as metal-based PCM [7].



(a) IVR-ERVC without PCM



(b) IVR-ERVC with PCM

Fig. 5 Visualization of the vessel wall and wall temperature according to the angle

4. Conclusions

To enhance the IVR-ERVC strategy, the two-layer cooling system with the phase change material (PCM) was suggested and investigated. The experimental study involved the visualization of the wall surface and temperature distribution of the vessel wall. Due to the latent heat of the PCM, the increase of the wall surface during the heat-up condition was mitigated. In steady state condition, the generated bubbles were decreased with the increase of the heat transfer area and the vessel wall temperature was dramatically increased. Therefore, the results show that the IVR-ERVC concept with PCM can be possible to enhance the thermal margin and suggest the new candidate of the IVR-ERVC. But, the consideration of the vessel failure was also needed. The further works are to determine the high thermal conductivity PCM for high-temperature application and to conduct the heat transfer test and visualization.

ACKNOWLEDGEMENTS

This work was supported by the Nuclear Energy Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT, and Future Planning. (No. NRF-22A20153413555)

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