HEAT REMOVAL CHARACTERISTICS OF IVR-ERVC COOLING SYSTEM USING GALLIUM LIQUID METAL

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ABSTRACT

The present work ultimately aims to develop the IVR-ERVC (In-Vessel Retention through External Reactor Vessel Cooling) system with enough thermal margin adopting liquid metal coolant as the severe accident mitigation system even for high power reactor. For the purpose, the conceptual design of IVR-ERVC with liquid metal is evaluated by performing an experimental campaign for a scaled facility. The specific geometry was devised to contain the liquid metal coolant facing with water through the container wall. Through this system, the heat transfer area is enlarged up to 2 times compared to the original area of the reactor vessel. This effect is also named as "liquid metal fin" in the current study. Improved heat transfer or reduced heat flux including large drop of focusing effect was confirmed by experimental results for a small-scaled facility to simulate the boiling phenomena under IVR-ERVC condition. It was found that significant reduction of focusing effect by liquid metal and extended surface area guarantee enough margin of successful IVR-ERVC without CHF issue even for large-sized power reactors.

KEYWORDS
IVR-ERVC, severe accident, corium, liquid metal fin, CFD

1. INTRODUCTION

In the light water reactors, a number of safety systems have been installed to prevent the progression of the accidents and return to the safety condition. However, although the safety systems have been established in the plants, some severe accidents happened due to the human errors and unexpected natural disasters. The representative examples of severe accidents are TMI [1] and Fukushima nuclear accidents [2]. There are a lot of reports analyzing the accidents to compare each other. There are many differences about the reactor type, generating capacity, containment building and causes of accident as well as accident progression. The most noticeable difference may be on the final location of the molten fuel. If the proper cooling systems could not be applied, the core material could be relocated to the bottom of reactor vessel. It is the natural movement of the corium which is the molten core material under severe accident condition. In the TMI nuclear accident, this corium was adequately cooled and certainly retained in reactor vessel. The progress of accident was finished in this step. When the proper cooling was not adopted under a severe accident, the corium could escape from the damaged reactor vessel. While the behavior boundary of radioactive materials was limited in reactor vessel in TMI accident, Fukushima nuclear accident caused even secondary damage such as ground water contamination which might occur with corium melt-through. The severe accidents really make difficult issues to deal requiring tremendous time and cost. The different results between TMI and Fukushima accidents give one of the most important lessons that the integrity of reactor vessel should be protected to minimize the spreading of radioactive materials through the broken 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]. This strategy has been adopted for the light water reactors such as Loviisa VVER, AP600, AP1000, and APR1400 through external reactor vessel cooling (ERVC). The main heat removal mechanism of IVR-ERVC condition is boiling heat transfer on the outer surface of reactor vessel. The function of this system is determined by the limitation of boiling aside from material issues related to temperature, stress, fatigue and creep. The limitation of boiling is 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.

The key concept of IVR-ERVC has been proposed and developed by Theofanous et al. [5, 6] and Dinh et al. [7]. Hemispherical test sections were designed to simulate the reactor vessel of AP600 and AP1000 with 2-dimensional geometry. The measured CHF data indicated that enough safety margin to CHF was ensured under severe accident conditions. These results were used to obtain the license for construction of the power plants.

Cheung [8] and Cheung et al. [9] studied and presented the design and concept to improve the heat removal capacity of IVR-ERVC on APR1400. The hemispherical vessel facility (Subscale Boundary Layer Boiling, SBLB) was used to conduct the CHF test. Obtained results contributed to changing the design of thermal insulator which is surrounding the reactor vessel. As the results, negative effects of shear keys on CHF could be reduced. Additionally, CHF enhancement was accomplished by optimized design of thermal insulator. Park et al. [10] established the experimental CHF correlation with mass flux and exit quality values. The test facilities were designed based on dimension of APR1400. Although it is required to consider the effects of scaled-down parameters and dimension, it is possible to predict a thermal margin to prevent the CHF with the CHF correlation. Park et al. [11] studied the effect of nanofliud on CHF under IVR-ERVC. When the graphene nanofluid was used as working fluid, CHF was enhanced about ~20% at all test conditions. So far, many researchers have reported the results of enhanced CHF when the nanofluid was used at CHF tests with a cylindrical tube. This CHF enhancement is not dependent on the geometry condition. It means that the additional thermal margin could be acquired by just adding the GO nanoparticles into the coolant without severe economic concerns.

Table 1 shows the applied mitigation strategies depending on the reactor type. The mitigation strategy can be divided into two types such as in-vessel corium cooling and ex-vessel corium cooling according to the position of the corium. In general, ERVC strategy gives sufficient thermal margin for small and medium-sized reactors like AP600 and AP1000. However, it is not certain whether the IVR-ERVC strategy provides enough thermal margin to prevent CHF phenomenon even for large-sized nuclear power plants which have a large-power capacity around 1500 MWe. One of the advantages of ERVC strategy is to prevent the release of radioactive materials from the reactor vessel during the severe accidents. It also simplifies the accident scenario by eliminating the direct containment heating (DCH), ex-vessel fuel-coolant interaction (FCI) and molten core concrete interaction (MCCI) which are complicated and still uncertain. The recommendations for increase of CHF include porous coating on the vessel outer surface, increasing the reactor cavity flood level and streamlining the gap between the vessel and the vessel insulation.

Recently, flooding the liquid metal into reactor vessel cavity was proposed conceptually by Park and Bang [12] to prevent CHF itself. Predicted heat flux, in particular, at the outer zone of reactor vessel with focusing effect of metal layer of corium formed in the inner vessel is beyond the critical heat flux under normal ERVC conditions of boiling heat transfer. Therefore, when the liquid metal is flooded into the cavity instead of normal water flooding for ERVC, the heat transfer mode is changed from two-phase of water to single-phase heat transfer of liquid metal. Although the heat was ultimately removed by boiling of water coolant in an additional inventory, the integrity of reactor vessel could be protected by reducing the focusing effect causing CHF occurrence. In this work, the UNIST liquid-metal experimental facility was designed and established to evaluate the concept of the liquid metal-based ERVC in terms of the improved heat transfer without CHF issues..

Table 1. Corium cooling strategy for each reactor type

Reactor type	Power (MWe)	Cooling type
EPR	1,700	Ex-vessel corium cooling
APWR	1,600-1,700	Ex-vessel corium cooling
ESBWR	1,600	Ex-vessel corium cooling
ABWR	1,400-1,600	Ex-vessel corium cooling
AES-2006	1,150	Ex-vessel corium cooling
AP600	600	In-vessel corium cooling
AP1000	1,000	In-vessel corium cooling
SWR1000	1,000	In-vessel corium cooling
APR1400	1,400	In-vessel corium cooling or Ex-vessel corium cooling

2. EXPERIMENTAL SETUP

2.1. Geometry of Test Section

Figure 1 shows the conceptual design for liquid metal-based ERVC system [12]. Additional container-like structure should be installed to keep the liquid metal with high density flooded around the reactor vessel. Also, this geometry was considered to reduce the amount of flooded liquid metal. This container is a hemispherical structure to completely cover the bottom of reactor vessel. A hollow cylindrical structure might be installed to enlarge the heat transfer area between the liquid metal and coolant. The size of this structure should be carefully determined because this issue is related to the location and the size of storage tank for liquid metal. The liquid metal can be stored in the inventory tank during the normal operation. The liquid metal can be injected to flood the cavity space for ERVC when the severe accident mitigation measures are taken. Before the corium is relocated to the lower plenum of reactor vessel, the liquid metal should cover at least the outside zone of bottom of reactor vessel. The minimum time interval between the start of core uncovery and the first relocation of corium is about 1000 s [13]. The required flooding time simply estimated using Eq. (1).

$$H(t) = (c - \frac{A}{2B}\sqrt{2g}t)^2 \qquad (1)$$

H (m) is distance between the exposed liquid metal surfaces of the storage tank and inner flooding structure. The A (m^2) is a cross-section area of a pipe or duct for transport of liquid metal. The B (m^2) is a cross-section of a storage tank. The c is a constant which is determined by the initial conditions. The g (m/s^2) is the acceleration due to gravity. The t (s) is the required time to fill the desired height. The required time limit (<1000 s) could be easily satisfied by changing the value of H, A, and B parameters. In actual situation, the type of liquid metal needs to be considered in terms of transport properties such as viscosity causing flow resistances

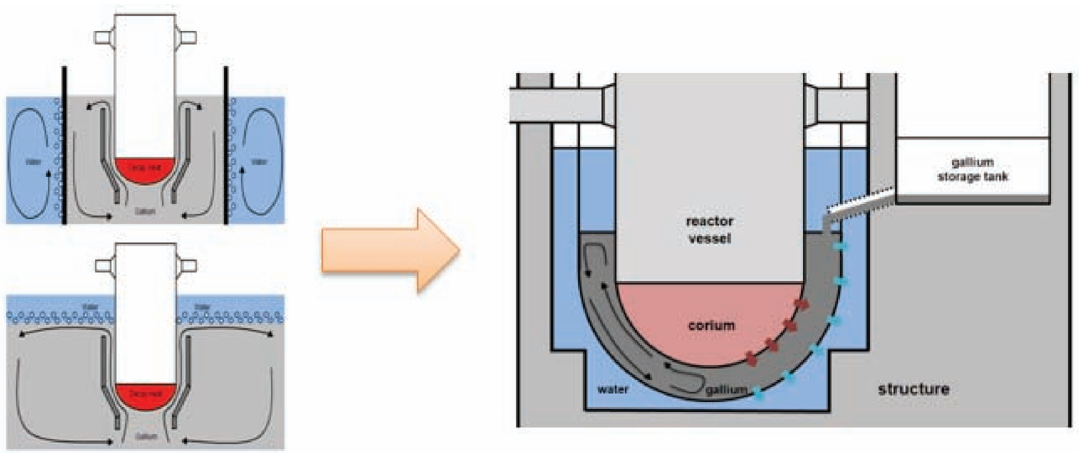
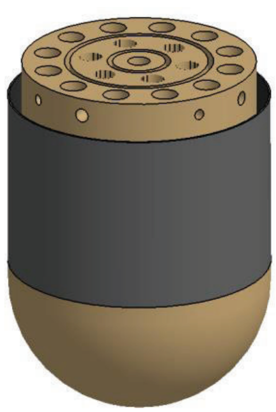
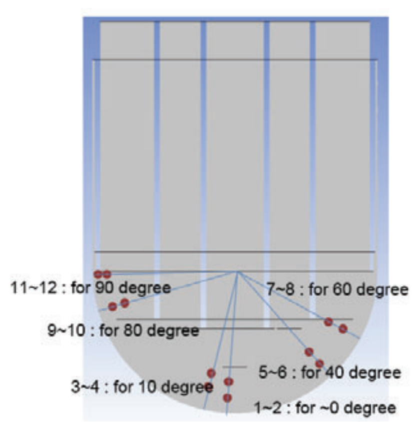


Figure 1. Conceptual design of IVR-ERVC with liquid metal [12]

2.2. Selection of vessel size and working fluids

Figure 2 shows cross section of a heated object. The simulated decay heat was generated from the cartridge heaters which was 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 is applied to this object via cartridge heaters. The refrigerant-123 is used as working fluid because CHF phenomenon can be studied at limited heat flux condition of the current facility capacity. R-123 has low boiling point (27.6 ^{o}C) and about 8 times lower than predicted CHF value of water. Therefore, it is possible to simulate the IVR-ERVC phenomena and compare differences between typical ERVC and liquid-metal ERVC strategies more realistically. The diameter size of the simulated vessel is 0.14 m. Gallium is used as liquid metal coolant. The melting point of this liquid metal is about 30 ^{o}C while its boiling point is about 2400 ^{o}C. The available temperature range of this metal is wide enough to operate as the heat transfer medium in a liquid phase. The thermal conductivity of gallium is about 50 times greater than one of water at 30 ^{o}C. This liquid metal is considered as a potential candidate for IVR-ERVC strategy with liquid metal.





(a) Test section (b) Cross-sectional surface

Figure 2. Heated object view and cross-section

There are three groups according to the arrangement of the cartridge heaters. Each group is separated from other groups by a gap as shown in figure 2. The outermost group is composed with 12 cartridge heaters. This group is called Group I. The 6 cartridge heaters were embedded in second layer. This group is called Group II. Group III is one cartridge heater located in the center. The gap acts as the insulator which is limiting heat transfer between the groups. Figure 3 shows the heat flux distribution obtained from the CFD results. Sequence of numbers is representing the groups. "0" and "1" mean power-off and full power respectively. The trend of heat flux profile corresponding to the corium configuration could be simulated by controlling the power of each heating group.

As shown in Figure 4, the experimental facility consists of test section, condensers, power controller, and data acquisition system. The input power was calculated by using the current and voltage indicated on the display of power controller. The temperature data were obtained from embedded thermocouples. Sudden temperature jump is estimated as CHF phenomenon. When the maximum temperature is beyond the design limit of material, the power could be automatically shut down to prevent the damage of cartridge heaters and heated object. The embedded thermocouples were located in 10, 20, 40, 60, 80, and 90 degrees on the basis of stagnation point which is the lowest point on the heated surface. Specific location of some thermocouple were described in Table 2. The temperature data obtained from these thermocouples are used to calculate the local heat flux and heat transfer coefficient on the surface of heated object. The local heat flux could be calculated by using Fourier's law. The heat transfer coefficient could be calculated based on the different temperature between the estimated copper surface temperature and gallium fluid temperature.

The first step for the test is to make the saturated and steady state for coolant at low heat flux condition. The first stage of heat flux is 10 kW/m^2. After reaching the steady state condition, a stepwise power escalation was initiated with increments of 10 kW/m^2 heat flux. Each power step lasted 10 minutes until a new steady state was achieved. In the liquid-metal test run, the filling height of liquid metal was 0.06 m.

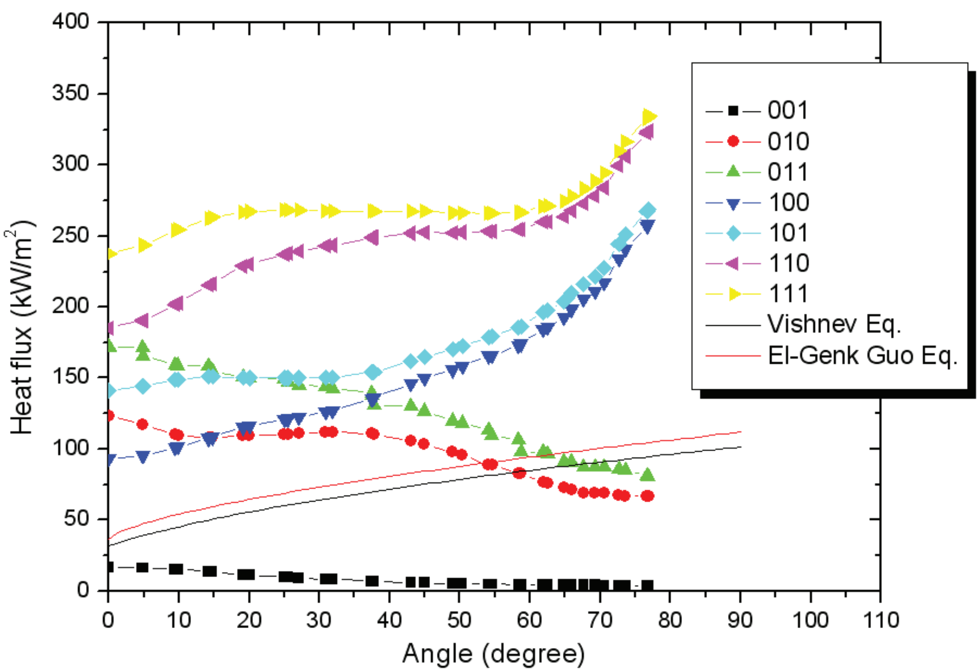


Figure 3. Heat flux distribution on the surface of heated object (CFD)

Table 2. Location of the thermocouples.

Number	Distance from a center of the hemisphere	Number	Distance from a center of the hemisphere
1	56	7	61
2	66	8	67
3	57	9	63
4	64	10	69
5	56	11	67
6	66	12	69

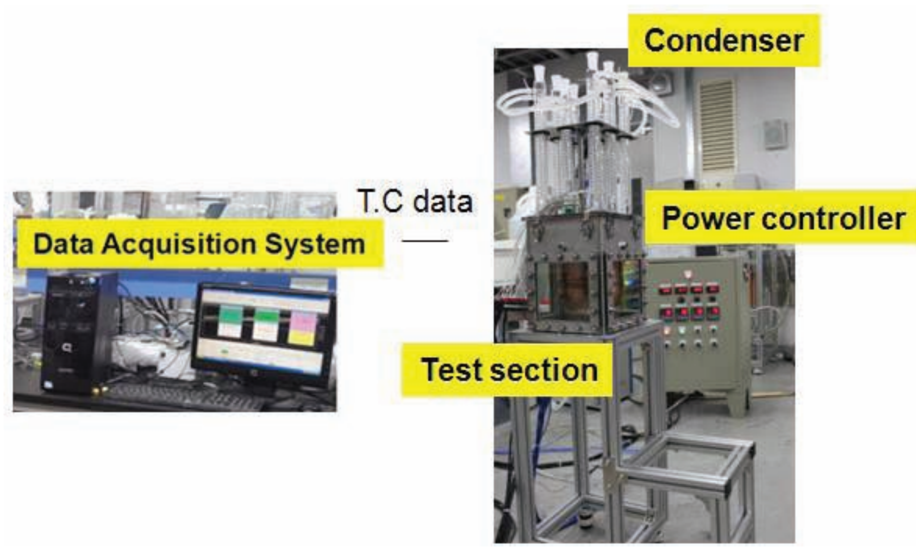
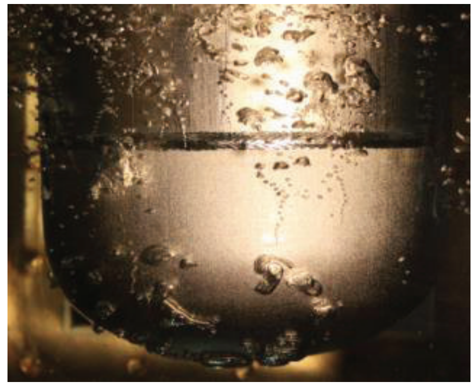


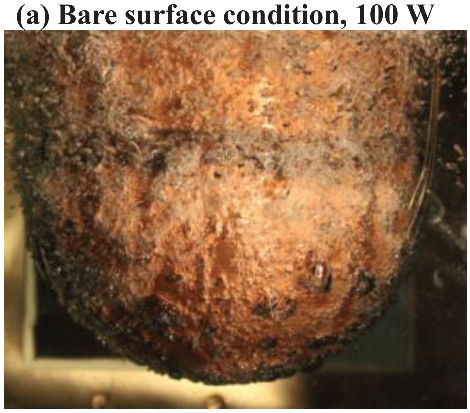
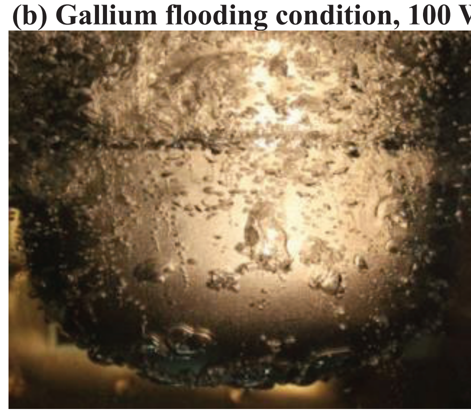
Figure 4. Test facility for IVR-ERVC with liquid metal

3. EXPERIMENTAL RESULTS AND DISCUSSION

Heat was ultimately removed by vapor formation regardless of flooding the liquid metal as shown in Figure 5. When the liquid metal was flooded as the new IVR-ERVC concept, vapor generation was decreased in comparison with typical IVR-ERVC system in which the surface of heated object was directly facing with the R-123 coolant because the heat transfer area was enlarged via liquid metal filled in the cap structure. The small-size bubbles merged into larger bubbles along with the heated surface. When the surface of heated object is directly exposed to the coolant, the surface temperature is quickly changed due to bubbles behavior. 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. In the liquid metal system, new heat transfer phenomena can be expected. Although the larger bubbles were formed on the surface of cap structure, heat also could be dissipated more quickly through the liquid metal itself. This heat dissipation phenomenon can prevent the local temperature rise or hot spot of heated object. Even though the enlarged heat transfer area is considered as the main factor to prevent CHF, delayed temperature response can contribute to enhancing critical heat flux.

(a) Bare surface condition, 100 W (b) Gallium flooding condition, 100 W

(c) Bare surface condition, 400 W (d) Gallium flooding condition, 400 W

Figure 5. Comparison of boiling phenomena between typical IVR-ERVC and new IVR-ERVC with liquid metal

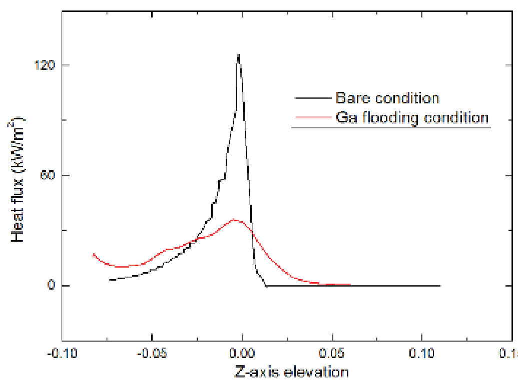
4. CFD ANALYSIS

4.1. Geometry and boundary condition

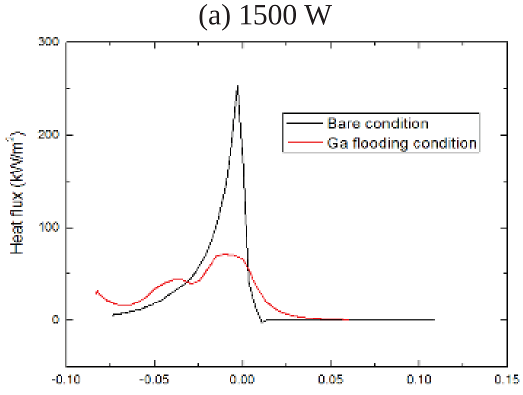
The experimental results are compared with CFD (ANSYS-CFX) analysis. The geometry for CFD analysis was a hemispherical shape. The geometry consists of SS cartridge heaters, cooper heated object, gallium liquid metal, and SS cap structure. The cartridge heaters were used to simulate the decay heat. The boundary condition for CFD was determined by considering realistic situation. Volumetric heat source was applied in the domains indicating the cartridge heaters. The cooling surface was set to have the constant temperature (32^{o}C) to simulate the boiling phenomena. Only cylindrical side and hemispherical surfaces were applied with this condition. The top surface of flooded gallium liquid metal was applied with the adiabatic wall condition. It is reflected in the experimental condition. k-ε turbulence model was used in the domain of gallium liquid metal. In the experimental condition, the contact resistance between the cartridge heaters and heated object is present. Wetting characteristics of liquid metal should be also considered because the contact condition between the liquid metal and structure is major factor to determine the heat transfer. In CFD simulation, there is no contact resistance in all interfaces. As the result of this setting, the temperature of CFD analysis is lower than one of experimental results about 5 K in the same position. It does not seriously affect to prediction of the local heat flux because overall temperature rise in the object are equally applied.

4.2. Characteristics of heat transfer

The liquid metal system was originally considered to prevent the CHF. Figure 6 shows the heat flux profile along the heated surface depending on the flooding conditions. After relocation of the corium into the bottom of reactor vessel in the severe accidents, the thin metallic layer is expected to be formed on the top of corium pool resulting in the focusing effect. The temperature of this layer is very high due to the poor radiation heat transfer. High heat flux to outer vessel wall is predicted due to this conduction layer. The focusing effect was reflected in the present work by controlling the location of cartridge heaters. When the heated surface was exposed to the coolant without the liquid metal, high heat flux was generated at top region of hemispheric (Z-axis: 0 m). However, when the liquid metal was flooded, this focusing effect was reduced. The reduction ratio is very noticeable when the heat flux condition is high. This result is surely owing to the enhanced heat transfer of flooded liquid metal. The heat transfer modes should be considered to understand the heat transfer characteristics induced by flooded liquid metal. The heat source is decay heat regardless of flooding conditions. The generated heat is transferred through the reactor vessel by conduction. The heat is removed by boiling on the outer surface of reactor vessel in the original IVR-ERVC strategy. On the other hand, the heat is also transferred to the liquid metal by convection. The top surface of flooded liquid metal might be directly facing with R-123 depending on a design option of flooding. Most of heat is finally removed by boiling on the outer surface of container to hold the liquid metal on flooding state. When the gallium liquid metal was flooded to enlarge the heat transfer area, maximum heat flux was reduced to about 3 times in comparison with the case of a bare surface condition. It means that safety margin to CHF phenomenon was secured for large-sized power reactor.



(a) 1500 W



(b) 3000 W

Figure 6. Significant reduction of focusing effect by liquid metal

Figure 7 shows the temperature distribution result of CFD analysis. The temperature of top region for flooded liquid metal is relatively lower than the temperature of other region. It means that the amount of heat transfer is negligible. This estimation is valid when the flooding height is enough high. If the flooding height is small, the exposed surface is maintained at high temperature. Active boiling heat transfer takes place on this surface. Two important insights could be obtained by analyzing temperature gradient. The traditional fluid has the constant ambient temperature. However, the high temperature gradient exists in the liquid metal because the thermal conductivity of liquid metal is high. It is caused by low Prandtl number of the liquid metal. Other insight is that the temperature of outer surface for reactor vessel is higher when the liquid metal was flooded. The medium of liquid metal layer exists between the reactor vessel and coolant. The overall heat transfer coefficient would be reduced due to the increased heat transfer resistance. The maximum temperature is about 150 ^{o}C in the case of bare condition. About 30 ^{o}C is increased in temperature when the liquid metal was flooded. The negative effect related to the temperature rise would enhance the ablation phenomenon inner surface of reactor vessel. The remained thickness of reactor vessel becomes thinner when the temperature of outer surface is increased. It is expected that the reduced thickness is not a serious concern because the inner temperature reaches the melting point of reactor vessel regardless of flooding liquid metal. Reduction of thickness can be relatively lowered according to the temperature difference between the inner and outer surfaces of reactor vessel.

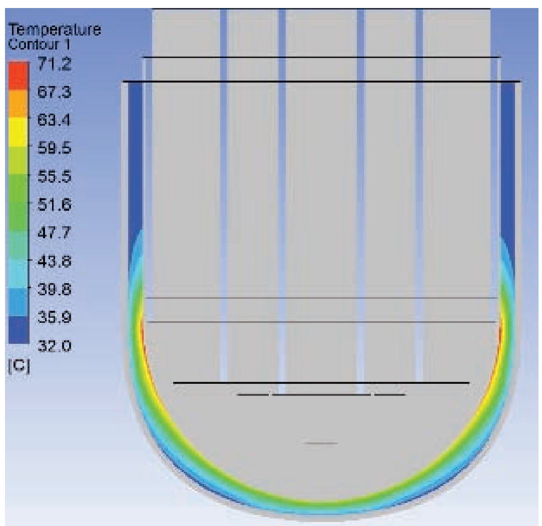


Figure 7. Temperature distribution on test section with liquid metal

5. CONCLUSIONS

The present work found that significant reduction of focusing effect by liquid metal and extended surface area guarantee enough margin of successful IVR-ERVC without CHF issue even for large-sized power reactors. Improved heat transfer or reduced heat flux including large drop of focusing effect was confirmed by experimental results for a small-scaled facility to simulate the boiling phenomena under IVR-ERVC condition. The scaled facility uses R-123 and Gallium. The heat transfer area is enlarged up to 2 times compared to the original area of the reactor vessel. This effect is also named as “liquid metal fin”. For further study, a variety of flow conditions and geometries will be considered for optimizing the effect.

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REFERENCES

1. G.A. Berna, G. Beyer, K. Davis, D. Lanning, “FRAPCON-3: A computer code for the calculation of steady-state, thermal-mechanical behavior of oxide fuel rods for high burnup,” *Nuclear Regulatory Commission*, Washington, DC (United States). Div. of Systems Technology; Pacific Northwest Lab., Richland, WA (United States); Idaho National Engineering Lab., Idaho Falls, ID (United States), 1997.
2. M. Holt, R.J. Campbell, M.B. Nikitin, “Fukushima nuclear disaster,” Congressional Research Service (2012)
3. T. Theofanous, C. Liu, S. Additon, S. Angelini, O. Kymäläinen, T. Salmassi, “In-vessel coolability and retention of a core melt,” *Nuclear Engineering and Design*, **169**, pp.1-48 (1997)
4. J. Rempe, K. Suh, F. Cheung, S. Kim, “In-vessel retention of molten corium: lessons learned and outstanding issues,” *Nuclear technology*, **161**, pp.210-267 (2008)
5. T. Theofanous, S. Syri, “The coolability limits of a reactor pressure vessel lower head, *Nuclear engineering and design*,” **169**, pp.59-76 (1997)
6. T. Theofanous, T.-N. Dinh, J. Tu, A. Dinh, “The boiling crisis phenomenon: Part II: dryout dynamics and burnout,” *Experimental Thermal and Fluid Science*, **26**, pp.793-810 (2002)
7. T. Dinh, J. Tu, T. Theofanous, “Two-phase natural circulation flow in AP-1000 in-vessel retention-related ULPU-V facility experiments,” *Proceedings of the 2004 international congress on advances in nuclear power plants-ICAPP'04*, 2004, Pittsburgh, PA USA, June 13-17, pp. 4242 (2004)
8. F. Cheung, “Limiting factors for external reactor vessel cooling,” *Nuclear technology,* **152**, pp.145-161 (2005)
9. J. Yang, M. Dizon, F. Cheung, J. Rempe, K. Suh, S. Kim, “CHF enhancement by vessel coating for external reactor vessel cooling,” *Nuclear engineering and design*, **236**, pp.1089-1098 (2006)
10. H.M. Park, Y.H. Jeong, S. Heo, “The effect of the geometric scale on the critical heat flux for the top of the reactor vessel lower head,” *Nuclear Engineering and Design*, **258**, pp.176-183 (2013)
11. S.D. Park, I.C. Bang, “Flow boiling CHF enhancement in an external reactor vessel cooling (ERVC) channel using graphene oxide nanofluid,” *Nuclear Engineering and Design*, **265**, pp.310-318 (2013)
12. S.D. Park, I.C. Bang, “Feasibility of flooding the reactor cavity with liquid gallium coolant for IVR-ERVC strategy,” *Nuclear Engineering and Design*, **258**, pp.13-18 (2013)
13. S. Oh, H. Kim, “Effectiveness of external reactor vessel cooling (ERVC) strategy for APR1400 and issues of phenomenological uncertainties, *Evaluation of uncertainties in relation to severe accidents and level*, **2** (2005).