Effects of Liquid Metal Fin on Critical Heat Flux under IVR-ERVC Condition

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1. Introduction

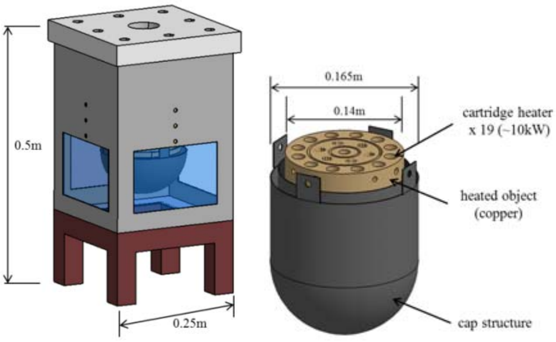
Severe accidents could occur when decay heat is not properly removed in a nuclear power plant. The molten fuel is relocated to bottom of reactor vessel after core is damaged and not cooled continuously. In-vessel retention through external reactor vessel cooling (IVR-ERVC) is presented to terminate the progression of accidents by removing the decay heat. IVR-ERVC is suitable for small size reactors like AR-600, AP-1000. There is uncertainty for high power reactor like APR-1400 and CAP-1400. This uncertainty originates from the thermal margin between the CHF value and real heat flux on the reactor vessel under severe accidents. The main mechanism of heat removal on IVR-ERVC strategy is boiling on the outer wall of reactor vessel. The boiling heat transfer is limited due to the CHF phenomenon. There should be an enough margin for preventing the CHF in boiling heat transfer systems. The CHF tests for IVR-ERVC system were conducted to confirm or increase the thermal margin [1, 2, 3, 4]. The design of thermal insulator was changed to vent the vapor smoothly. Forming the coating layer on the vessel surface was proposed to enhance the CHF margin. The some concerns arises how to guarantee the integrity of coating layer and enhanced CHF data at the coolant condition. Coolant is already contaminated with some suspended solid and chemicals. The CHF data which is conducted under well controlled condition might deteriorate terribly. New approach was presented to use the liquid metal to avoid these issues [5]. The liquid metal was designed to flood the space around the reactor vessel. The liquid metal has high boiling point and superb thermal conductivity in comparison with the coolant.

In this work, experimental tests were conducted to validate the CFD results about the IVR-ERVC system with liquid metal. The behavior of vapor was observed to predict the tendency of CHF increase with small-scaled facility to simulate the IVR-ERVC system.

2. Experimental setup

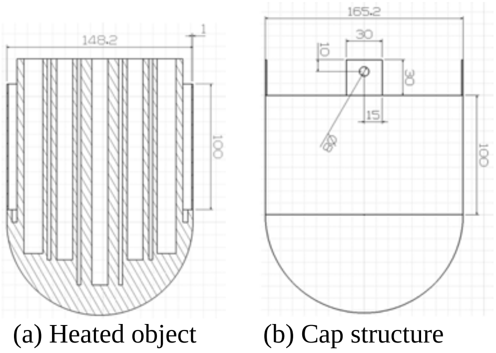
2.1 Design of the test section

The test facility should be designed to simulate the characteristics of liquid metal flooded IVR-ERVC. The key parameter to determine the capability of heat transfer is the height of flooding liquid metal. It is important to change the value of this parameter. Figure 1, 2 show the geometry and dimension of test section reflecting this requirement. The size of the heated object is determined by the allowable electrical power input. The heating object is made by copper material. A lot of cartridge heaters were insulted in the copper object to simulate the decay heat. There is an uncertainty to determine the heat flux profile on the reactor vessel under severe accidents under IVR-ERVC condition. A variety of heat flux profile should be generated to make up this uncertainty. The heating zone is divided 3 parts. Each part has individual cartridge heater. By controlling the amount of heat energy, the heat flux could be controlled sophisticatedly. The capable heat flux profile is shown in Fig. 3. The CFD simulation was conducted to confirm the heat flux profile on the surface of cooper heated object with a dimension of test section. The volumetric heat source and boiling condition was set as boundary condition. The symbols of “1” and “0” mean whether or not the power is supplied. The test section was designed to reflect the focusing effect. The heat flux of the high angle part is higher than one of other position because of the consideration of the focusing effect.



(a) Overall view (b) test section

Fig. 1. Geometry of test facility



(a) Heated object (b) Cap structure

Fig. 2. Design of components

The heated object is composed with the hemispherical and cylindrical geometry. The heat is transferred from the cartilage heater directly on hemispherical surface. However, heat is transferred from the hemispherical part on surface of the cylindrical geometry. The conduction heat transfer mode is mainly effective on cylindrical part. It is exactly similar to real situation and suitable to confirm the effects of flooded liquid metal. Present design could simulate the enlarged heat transfer area caused by flooding the liquid metal.

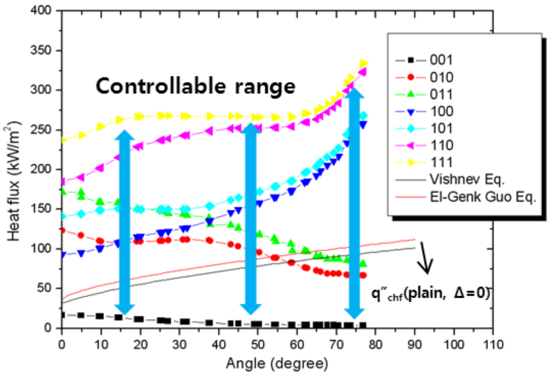


Fig. 3. Heat flux profile in all heating conditions

The maximum heat flux on the hemispherical surface is about 350 kW/m^2. It is required to select the simulant to conduct the CHF test. The working fluid was replaced from water which is present coolant in real IVR-ERVC strategy to R-123 refrigerant. The predicted CHF value is about 200 kW/m^2 on the pool boiling condition at saturation state under atmospheric pressure condition. This value is about 1/5 of CHF for water at same condition [6]. The CHF occurrence could be observed at relative low heat flux on IVR-ERVC system with R-123 refrigerant. The gallium was selected as flooded liquid metal. The melting temperature of gallium is close to room temperature. The gallium is easily manageable without vigorous chemical reactions and the toxic components at usable temperature range.

2.2 Experimental apparatus and test condition

Figure 4 shows the test facility. It is composed with the heating element, the condenser, power controller, data acquisition system. 19 cartridge heater (500 W) and 15 thermocouples (K-type) were embedded to copper heated object. The local heat flux could be calculated with the temperature date obtained from 12 thermocouples. The positions are 10, 20, 40, 60, 80, 90 degree on the basis of stagnation point which is the lowest point on the heated surface. Other function is to detect the CHF phenomenon. These thermocouples are located near the boiling surface. The prompt reaction about the sudden temperature jump could be checked by monitoring the temperature data. 3 thermocouples are located to near the cartridge heater of each part. The purpose of these thermocouples is to protect the damage of heater from unrecovered temperature limit.

The meaning of the height for the flooded liquid metal is mentioned previously. The cap structure could separate the region of the liquid metal from the surrounding coolant. The hemispheric area of this cap structure is 1.25 times compared with the area of bare heated copper object. The maximum flooding height is 10 cm from the reference line which is change point of the geometry from the hemisphere to cylinder. Flooding height is set as 6 cm in the tests. Heating condition is 50, 100 kW/m^2. These values are calculated from dividing the total heat by the hemispherical area of copper object.

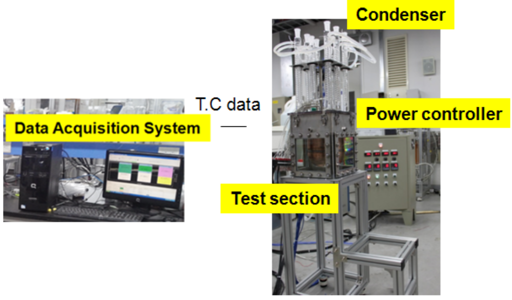
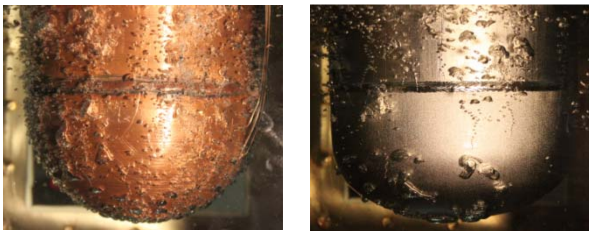


Fig. 4. System for IVR-ERVC test

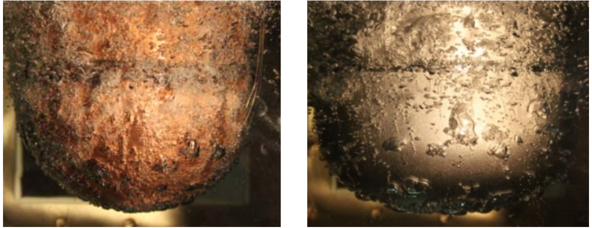
3. Results and discussion

Figure 5 shows the behavior of bubble on the heated surface. The amount of generated vapor per unit area is reduced when the cap structure was installed at same heat flux condition. This phenomenon was clearly caused by enlarged heat transfer area. The level of heat flux on specific area which is influence with focusing effect could be reduced as shown in Fig. 6. It means that an enough thermal margin is guaranteed under severe accidents for high power reactor.

Boiling occurs continuously on the local region which has some cavities at 50 kW/m^2 condition. The geometry of cap structure is not perfectly hemispheric. Especially, the shape of lower section in the geometry is relatively flat. The bulk vapor is formed on heated surface of cap structure due to the low rising velocity. This effect is negligible when more heat was generated.



(a) bare, 50 kW/m^2 (b) Gallium, 50 kW/m^2



(c) bare, 100 kW/m^2 (d) gallium, 10 kW/m^2

Fig. 5. Vapor behavior on the heated surface

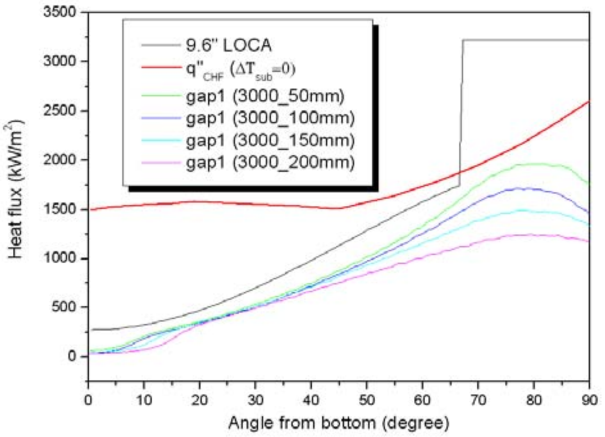


Fig. 6. Heat flux distribution according to the position on heated wall

4. Further work

In this work, the CHF simulation and validation tests were conducted as the extension of the study submitted to the 2014 KNS Autumn Meeting [7]. The amount of generated vapor was reduced when the cap sturecutre was installed with flooded liquid metal. The test results shows that issued problem about the thermal margin is resolved by flooding the liquid metal to enlarge the heat transfer area. Additional tests will be conducted at a variety of conditions about the flooding height, heat flux.

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