Transactions of the Korean Nuclear Society Autumn Meeting
Gyeongju, Korea, October 25-26, 2012

CHF Enhancement by Graphene-oxide Nanofluid for External Reactor Vessel Cooling Strategy

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1. Introduction

In-vessel retention (IVR) of molten core as an important severe accident management strategy has been adopted for the advanced light water reactors (ALWRs) such as AP600, AP1000, and APR1400 through external reactor vessel cooling (ERVC). To manage the accident that core melts and deposits on the bottom of reactor vessel, ERVC begins to flood the reactor cavity to remove the decay heat through the wall of the reactor vessel. Therefore, ERVC prevents the escape of radioactive materials from the reactor vessel strongly during the severe accidents. It simplifies the severe accident scenarios. Another advantage of ERVC is to improve the plant economics by reducing regulatory requirements. The heat removal of ERVC is restricted by thermal limit called by critical heat flux (CHF). Besides, thermal design power of nuclear power plants has been increasing for the economics. This trend causes the decrease of the thermal safety margin. Therefore, it is essential to obtain an enough safety margin in terms of CHF values. Up to now, a few investigations have been performed to evaluate and increase the coolability of ERVC [1,2,3,4].

2. Experimental Methods

2.1 Preparation of test fluid

The modified Hummers method [5] is used in preparing the graphene oxide nanofluid. In this process, the graphene was formed from the graphite by some of chemical steps. The graphite is manufactured by Sigma Aldrich Corporation (graphite powder, size < 45μm). The concentration of graphene oxide nanofluid is 10^{-4} V%. Eq. (1) is used to calculate the volume concentration of nanoparticle in nanofluids

$$\varphi_v = 1 / \left[\left(\frac{1-\varphi_m}{\varphi_m} \right) \frac{\rho_p}{\rho_f} + 1 \right] \tag{1}$$

where φ_m is the mass concentration of nanoparticles, ρ_p is the nanoparticle density, ρ_f is the liquid density.

2.2 Experimental apparatus and procedure

A schematic diagram of the experimental apparatus is shown in Fig. 1. The experimental facility loop consists of reservoir tanks, pump, flow meter, preheater, condenser and test section. The material of test section was stainless steel 304. The radius of curvature was 100mm which is the size in 1/16 scale down of the APR-1400 design. The heater shape is quarter-circle. The dimension of each part in test section simulated the APR-1400.

In this test, direct joule heating was used to heat the test section. A heat flux was calculated by using Eq. (2). As shown in Fig. 2, the stainless steel 304 was welded with the copper electrodes which are connected with a power supply. The voltage between the both sides of test section (stainless steel 304) was directly measured when the electricity flowed. The exact electrical resistance of test section was obtained by using Ohm's law under the condition which is fully aware of the current and voltage. An effective area is limited on a part of stainless steel 304 in contact with water. The other side was insulated to prevent the heat loss. In addition to that, the test section was whole surrounded by the insulation. The thermocouples were attached on the outside of the heater surface to measure the CHF phenomenon.

$$q'' = \frac{V^2}{RA_{eff}} \tag{2}$$

where q" is the average heat flux, V is measured voltage, R is electrical resistance, A is the area of the test section facing to water.

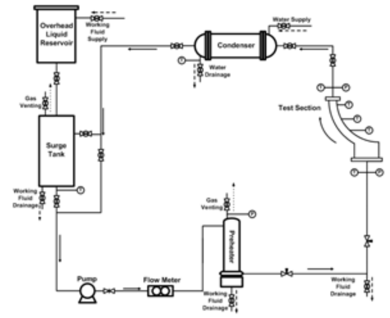

Fig 1. Schematic diagram of the experimental loop

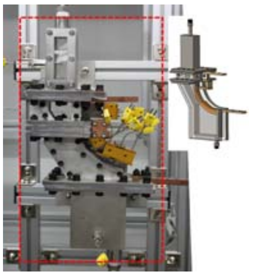

Fig 2. Geometry of test section

Table I : The experimental conditions of this study

Heater radius(mm)	100
Test section gap size(mm)	20
Heating method	DC heating
Circulation method	Forced circulation
Pressure (kPa)	101.3
Mass flux(kg/m^2s)	50, 100
Inlet subcooling(K)	10
Minimum gap point(degree)	56.6
Working fluid	DI water, graphene oxide

In ERVC condition, the natural circulation occurred between the reactor vessel outer wall and the surrounding insulation. To simulate this condition, the pump was used to control the mass flux passing over the heater surface. Table I shows the experimental conditions of this study.

3. Results and Discussion

In this study, inlet subcooling conditions were 10K. And mass flux conditions were 50 and 100kg/m2s. Working fluid was distilled water and graphene oxide nanofluid (concentration: 10^{-4}V%). The experimental results for CHF enhancements under subcooling 10K at atmospheric pressure are shown in Fig. 3. Whether or not the CHF occurs was estimated by the sudden jump in temperature. This phenomenon shown in Fig 4 was observed in all cases. The thermocouples were attached by the compressed spring forcibly not a welding. The sudden decrease of the measured temperature at about 1300 second could be caused by the condition of the heater outer surface as shown in Fig 6. The CHF occurred on upper region of the test section in all test cases. It means that effects of the minimum gap in the test facility are not critical on the CHF. The CHF results were increased as increasing the mass flux. CHF limits for water are consistent with the results of KAIST and ULPU configuration II at same test conditions.

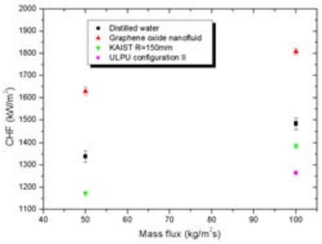

Fig 3. CHF results according to mass flux at subcooling 10K condition.

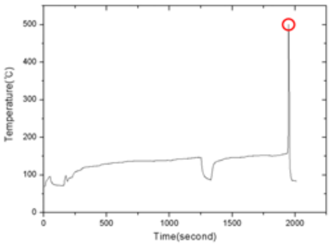

Fig 4. Result of measured temperature on the heater surface.

The interesting results are that CHF limit was enhanced when the graphene oxide nanoparticles were dispersed in the working fluid which is called as graphene oxide nanofluid. The CHF of graphene oxide nanofluid was about 1600kW/m^2 when the mass flux 50kg/m^2s. And the CHF of graphene oxide nanofluid was about 1800kW/m^2 when the mass flux 100kg/m^2s. Tests were conducted three times for each flow condition. A new test section was used for each test.

After flow boiling experiments, build-up layers are observed on the heater surface as shows in Fig 5. The upper part of coating layer on the heater surface was removed by the CHF phenomenon. The graphene oxide nanoparticles do not completely cover the heater surface due to the some gloss which was observed on the surface. Although the coating layer was not formed homogeneously, this layer caused the CHF enhancement.

Fig 5. Heater surface from before and after the CHF test

4. Summary and Conclusions

To ensure the safety margin for in-vessel retention by external reactor vessel cooling, the flow boiling test was performed by graphene oxide nanofluid as a base fluid which is surrounding the heater.

The following results are obtained.

(1) When the graphene oxide nanofluid was used as a base fluid, the critical heat flux (CHF) was enhanced in comparison with the distilled water during the flow boiling.

(2) After the CHF, a thin coating layer was observed on the heater surface in case of the graphene oxide nanofluid to be used. It is caused by the boiling phenomena.

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