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# Effects of Nanofluid for In-Vessel Retention External Reactor Vessel Cooling on Critical Heat Flux using Pool Boiling Experiments

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## 1. Introduction

In-vessel retention (IVR) is one of the severe accident management (SAM) strategies that are used in some nuclear power plants; AP600, AP1000, Loviisa and APR1400. One way of IVR is the method of external reactor vessel cooling (ERVC). When core melts and deposits on the bottom of reactor vessel, ERVC is starting to flood the reactor cavity to remove the decay heat through the wall of the reactor vessel. This process can improve the plant economics by reducing regulatory requirements. And increased safety margin leads to gain public acceptance. In this system, the heat removal is restricted by thermal limit called by critical heat flux (CHF). Besides, as advanced light water reactors such as South Korea's APR-1400, thermal safety margin is deceased. So, it is essential to get more safety margin. There are some approaches to enhance the ERVC [1]; usign the coatingon on the vessel outer surface, increasing the reactor cavity flood level, streamlining the gap between the vessel and the vessel insulation. Many investigations have been performed to evaluate the coolability of IVR [1, 2, 3, 4, 5]

In this paper, we firstly investigated the coating effects in the critical heat flux among the above mentioned approach methods. During the boiling phenomenon, a thin layer was formed on the heater surface in the nanofluid. This coating mechanism is well known theoretically [6]. Nanofluids are colloidal dispersions of nanoparticles in traditional heat transfer fluids. One of the most interesting characteristics of nanofluids is their capability to enhance the critical heat flux (CHF) significantly. Nanofluid is made by typical particle materials. Materials of nanoparticles include metals (e.g., silver, copper, gold), metal oxides (e.g., titania, alumina, silica, zirconia), carbon allotrope (e.g., carbon nanotube, graphite). We selected the graphene-oxide nanofluid which is a kind of carbon allotrope. Graphene-oxide is attractive material with the high thermal conductivity and stable dispersion ability in the distillated water [7].

## 2. Description of experiment

### *2.1 Preparation of test nanofluid*

Graphene oxide nanofluid is prepared from graphite as shown in Fig. 1. In this work, used graphite is manufactured by Sigma Aldrich Corporation (graphite powder, size < 45μm). Modified Hummers method is used in preparing the graphene oxide nanofluid [13]. The concentration of graphene-oxide nanofluid is 0.0001V%. Eq. (1) is used to calculate the volume concentration of nanoparticle in nanofluids. Graphene-oxide nanofluid mixed with boric acid, lithium hydroxide and tri-sodium phosphate to investigate the dispersion stability. The mixing of test fluids was made separately and together.

Fig. 1. Graphen-oxide nanofluid at 0.0001v%

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

Where $\Phi_m$is the mass concentration of nanoparticles, $\rho p$ is the nanoparticle density, $\rho f$ is the liquid density.

### 2.2 *Experimental procedure*

A schematic diagram of the experimental apparatus is shown in Fig. 2. The pool test facility consists of rectangle vessel (100mm × 50mm × 120mm), copper blocks, Teflon cover, reflux condenser, power supply, and data acquisition device, hot plate and standard resistor. The concentration of nanofluid is maintained by the Teflon cover and the reflux condenser. Data obtaining from the data acquisition device which is connected to the upper part of electrodes and standard resistor is saved and analyzed. The heating method on test section is joule heating through the wire. The material of heating wire is nickel-chrome (80/20, L=55mm, R=0.49mm).

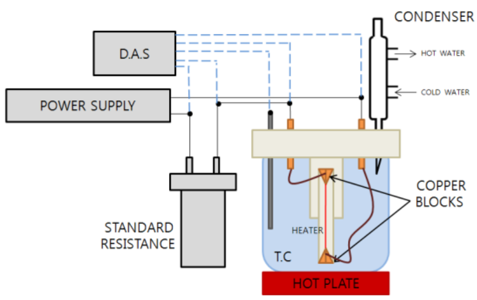


Fig. 2. Schematic diagram of the test facility

Tests were conducted at 0, 30, 60 and 90 degree of heater inclination under saturated temperature and atmospheric pressure. The heater was designed to be able to rotate the inclination. To consider the heat loss about every kind of an electric conductor but nickel-chrome wire, we calculated the system resistance. Eq. (2), (3) were used to calculate the average heat flux.

$$R_w = V/I - R_s \qquad (2)$$
$$q'' = I^2 R_w/\pi DL - R_s \qquad (3)$$

Where q" is the average heat flux, V is measured voltage, I is measured current, $R_w$ is wire resistance, $R_s$ is system resistance excluding the wire resistance. D is the diameter of wire. L is the length of heated wire.

## 3. Results and discussion

To test the credibility of the test facility, we performed the critical heat flux test using the distillated water at 0, 30, 60, 90 degree of heater inclination under saturated temperature and atmospheric pressure. Fig. 3, 4 show the results of the CHF for graphene-oxide nanofluid and solutions. These chemicals have each function and concentration in solution to operate the nuclear power plant. Boric acid is used to control the fission reaction for preventing the supercritical condition. The pH value is controlled by adjusting the lithium hydroxide in the primary coolant. The tri-sodium phosphate adds to hold the volatile fission products.

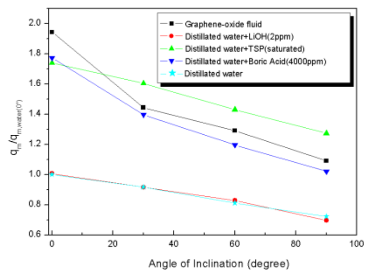


Fig. 3. Effects of orientation on CHF for graphene-oxide nanofluid and solutions

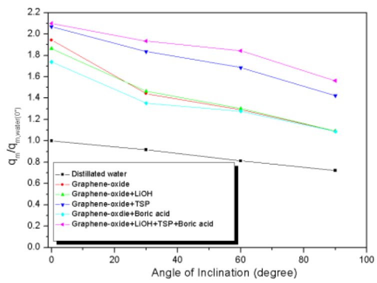


Fig. 4. Effects of orientation on CHF for graphene-oxide nanofluid with solutions

CHF is enhanced when graphene-oxide nanoparticle and other soluble chemical are added in distillated water. Only enhancement of CHF is not occurred in LiOH solution. It is the concentration of the solution is low. And highest CHF enhancement is occurred when all soluble chemicals are added in graphene-oxide nanofluid.

## 4. Summary & Conclusions

To ensure the safety margin for in-vessel retention by external reactor vessel cooling, the pool boiling test was performed by graphene-oxide nanofluid as a base fluid which is surrounding the heater. Tests were conducted at 0, 30, 60 and 90 degree of heater inclination under saturated temperature and atmospheric pressure. And the effects of CHF was investigated when graphene-oxide nanofuid was mixed with boric acid, lithium hydroxide (LiOH) and tri-sodium phosphate (TSP).

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 distillated water during the pool boiling. Enhanced ratio is decreasing, as bigger heater inclination is applied from 0 degree to 90 degree.

(2) After the CHF, a thin coated wire 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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