CHF Experiments with Micron-sized Amorphous and Porous Particles on Plate-shaped Heater for Development of Multi-functional Magnetic Nanoparticles

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1. Introduction

A severe accident in nuclear power plants (NPPs) occurs when nuclear fuel melts, which may lead to the leakage of radioactive materials to environment. It is important to keep the radioactive nuclides inside the containment of NPPs for public safety. As one of the countermeasures against the severe accidents, the concept of multi-functional magnetic nanoparticles (MFMNs) was proposed [1]. As shown in Fig. 1, MFMN consists of a magnetite nanoparticle and a porous silica layer located in the center and around of it, respectively. The MFMNs have three main advantages. First, they can capture radioactive materials like cesium ions released out during the accident. Second, they can be magnetized by external magnetic force, so that the MFMNs can be separated from the suspension after usage. Third, they can enhance thermal margins of safety systems such as In-vessel retention of molten corium through external reactor vessel cooling (IVR-ERVC) and core capture. Consequently, the MFMNs prevent the radioactive nuclides from escaping out of NPPs and increase public safety as a severe accident mitigation strategy. On this basis, for the optimized design for MFMNs, various researches have evaluated the absorbability, magnetic properties, and heat transfer characteristics depending on the dimension of magnetite and silica particles. In this study, porous silica particles located outside of MFMN are focused on, which are responsible for the change of a surface morphology. The silica particles deposited on the surface will affect the heat transfer and critical heat flux (CHF) that should be evaluated for applications in industry. Thus, pool boiling experiments with porous and amorphous silica particles were conducted to investigate the pore size effects on the CHF.

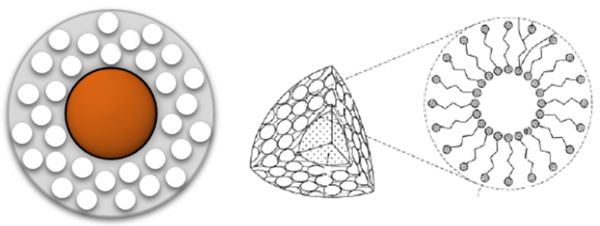

Fig. 1. Schematic figures of multi-functional magnetic nanoparticles (Centered: magnetite particle, Surrounding: porous silica particle shell)

2. Experiments

2.1 Apparatus for pool boiling experiments

The experimental facility for the tests was designed to measure CHF values as shown in Fig. 2. As a test section, plate-shaped stainless steel heaters were used, and an adiabatic condition below the heater surface using silicon rubbers. Through a rectifier and a copper electrode, direct voltage was induced on the heater. The voltage, the current, and the temperature of the heater were measured by data acquisition device (DAQ). The data measured were used to calculate the heat flux generated on the heater, and the CHF was defined as the heat flux when the rapid increase of temperature was observed. In addition, we performed the experiments at the atmospheric pressure and the saturation temperature by controlling a preheater and a condenser.

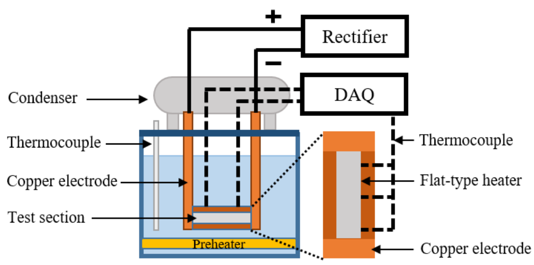

Fig. 2. Experimental apparatus for pool boiling test

2.2 Silica particles and suspension

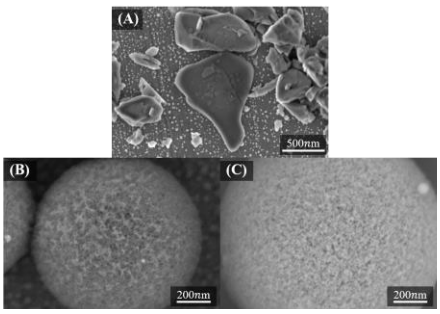

Fig. 3. Images of (A) amorphous and porous silica particles with pores of (B) 2nm and (C) 4nm

Amorphous silica particles, and porous silica particles with pores of 2nm and 4nm were prepared for the tests. The average size of all the particles is 1μm. More specifically, figure 3 depicts the particle dimension through scanning electron microscope (SEM). It is observed that the porous particle has innumerable pores on itself, which has much larger surface area than the amorphous particle. In other words, the porosity of porous particles is expected to greatly influences the heat transfer mechanisms by improving wetting ability.

Silica particle suspension for the experiments was manufactured by mixing the silica particles into deionized water (two-step method) and conducting sonication process using ultrasonic bath. Moreover, based on previous studies, it has been verified that the sonication process ensure the good stability with above 30 mV of zeta potential [2–4]. Considering the works on nanofluid stability, the stable suspension with a concentration range from 0.1ppmv to 10ppmv was manufactured.

3. Results

Experiments were conducted 3 to 5 times depending on the kind of particles and the concentration regions. Figure 4 shows the effects of amorphous particles and porous particles on the CHF according to the concentration. Regarding all the silica particles, almost no change of CHF values was observed at low concentrations, while the CHF values were improved in high concentration regions of 10ppmv. Furthermore, much higher CHF values were observed in the case of the porous particles than that of the amorphous particles in 10ppmv-concentration regions.

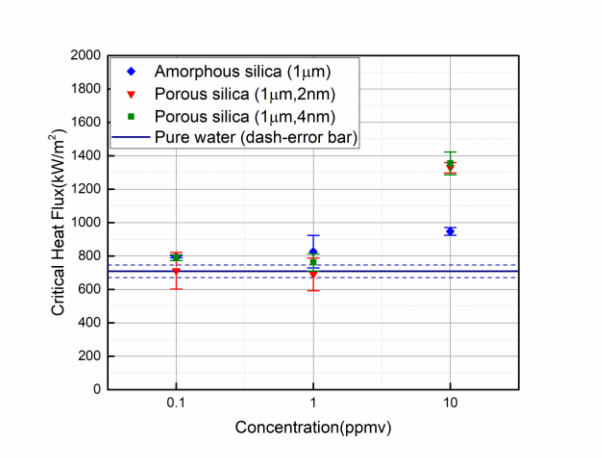

Fig. 4. Results of CHF experiments depending on pore size and concentration

With the heaters used in pool boiling tests, surface analyses were conducted through contact angles and SEM images to analyze the CHF improvements. As depicted in Fig. 5, contact angles were measured by dropping 5μL of deionized water on heater surface where silica particles had been deposited. Compared with the case of pure water, contact angles decreased little at 0.1ppmv-concentration in the case of all the particles. Meanwhile, the porous particles have even higher CHF values than the amorphous particles in 10ppmv of concentration regions. In detail, a little improvement of contact angles was observed for the amorphous silica particles as the CHF values were enhanced a little at 10ppmv-concentration. Whereas for the porous particles, much lower contact angles and higher CHF values were observed at 10ppmv-concetnration. It proves that the porous particles, which have a much larger surface area than the amorphous ones, enhanced wettability of the surface and positively influenced CHF mechanisms.

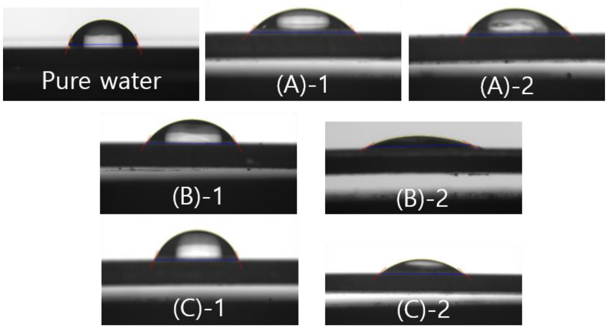

Fig. 5. Images of contact angle for heaters tested with pure water, (A) amorphous particles, (B) porous particles with 2nm of pore, (C) porous particles with 4nm of pore in (1) 0.1ppmv and (2) 10ppmv of concentration region

As presented in figure 6, it is confirmed that silica particles were deposited well on the heater surface where the experiments had been conducted in 10ppmv of concentration regions. The deposition can account for the variation of contact angles and CHF values. No formation of a porous layer on the surface was confirmed for the amorphous particles, although the numerous particles are deposited (Fig. 6-A). This morphology change lead to a little increase in the wettability and the CHF. On the contrary, regarding porous particles, porous layer was observed on the surface (Fig. 7-B, C). The porous structure, wettability improvement and large surface area of porous particles enhance the ability of wetting and cooling the heater surface, and it enables the CHF to increase a lot.

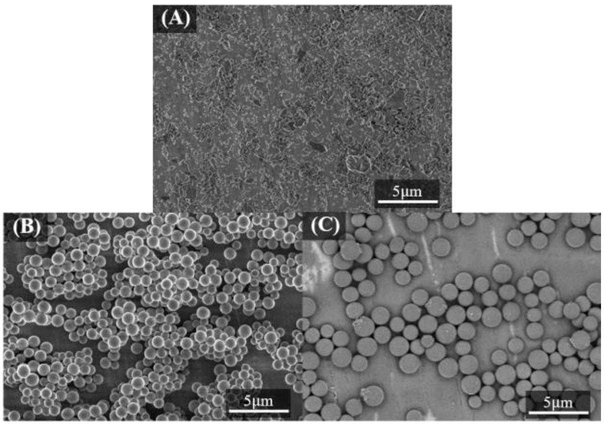

Fig. 6. SEM images of heater surface after experiments with suspension in 10ppmv of concentration((A): Amorphous particles, (B): Porous particles with 2nm of pore, (C): Porous particles with 4nm of pore)

4. Conclusion

To design optimized MFMNs, CHF experiments with amorphous and porous silica particles were conducted to evaluate heat transfer characteristics depending on size and shape of the particles. In addition, based on the CHF results, surface analyses were conducted with morphology evaluation of heater surface using SEM images and contact angle measurements. As results, in low concentration regions of 0.1ppmv and 1ppmv, there was no distinctive change of CHF values despite a little increase in wettability. On the other hand, in high concentration regions of 10ppmv, the improvements of CHF values were confirmed up to 200% compared with CHF values obtained when pure water was used for the tests. Furthermore, porous particles show much higher CHF enhancements than amorphous particles at 10ppmv of concentration. This is due to large surface area of porous particles, and the formation of porous structures by particle deposition. The surface morphology change can efficiently cool the heater surface and improve CHF. However, the particles with 2nm and 4nm of pore show similar CHF values, while they have a different surface morphology and a surface area. It seems that there will definitely be more dominant parameters than the surface area. Thus, the additional experiments using various sizes of porous particles are highly required to analyze the impacts of the porous particles on boiling and heat transfer mechanisms.

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