A feasibility study of application in NPPs using magnetite-water nanofluid

Jong Hyuk Lee [a], Dong Hoon Kam [b], Yong Hoon Jeong [b*]
[a]*Thermal Hydraulics Safety Research Division, KAERI, 989-111 Daedeok-daero, Yuseong-gu, Daejeon, 305-353, Republic of Korea*
[b]*Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology, 291, Daehak-ro, Yuseong-gu, Daejeon, 305-701, Republic of Korea*
**Corresponding author: jeongyh@kaist.ac.kr*

1. Introduction

A primary interest with regard to nanofluids is on heat transfer without phase changes. The researches of heat transfer using nanofluids are extended to boiling heat transfer because of the most effective heat transfer of boiling with phase changes. However, it exists the limit of effective heat transfer, so called as critical heat flux (CHF), which can be generated from nucleate boiling to film boiling. Many researches have been tried to evaluate the CHF with several kinds of nanofluids and, they concluded that CHF can be improved with nanofluids containing a very small volume fraction of nanoparticles [1-4].

However, it is not easy to apply excellent heat transfer of nanofluids into the nuclear systems, which are normally operating at very high pressure (~70 bar) and temperature condition (~550℃). Because of these severe conditions, the further study on characteristic feature of nanofluid should be required to assess the feasibility of the uses of nanofluids in nuclear systems.

We expected that nanofluids could be a potential future application in nuclear power plants as a coolant in the emergency cooling system. Especially, it is expected that nanofluids could be used to enhance in-vessel retention (IVR) capability in severe accident mitigation strategy due to high CHF margin of nanofluids.

In order to assess the thermal performance the pool boiling CHF experiments were performed. And magnetite-water nanofluids were used in this study. This study was focused on the relation between the CHF and nanofluid stability to evaluate the feasibility of nanofluids in nuclear power plants. The detailed studies on the effect of nanofluid stability will be discussed in this study.

2. Assessment of nanofluid stability and CHF

To guarantee the performance of nanofluids, it is required to evaluate the nanofluid stability. The heat transfer performance is dependent upon the nanofluid stability. In order to clarify the relation between the nanofluid stability and heat transfer performance of nanofluids, the effects of sonication, dilution, and storage time were considered and magnetite-water nanofluid was selected in this study.

And, pool boiling CHF experiments using Ni-Cr wire were performed. The detailed experiment apparatus and procedure are refer to previous study [5].

2.1 The effect of sonication

An advantage of two-step method for manufacturing the nanofluids is that nanoparticle produced in bulk at low prices can be used. The manufacturing process of nanoparticle powders is very simple. However, it is inevitable that individual particles quickly agglomerate before dispersion. Therefore it is expected that initial sonication should be necessary to disperse the nanoparticles in a fluid. To understand the effect of soincation for manufacturing of nanofluid on CHF, two kinds of nanofluids were prepared. One is magnetite nanoparticle is well dispersed ultrasonically in a pure water and the other is magnetite nanoparticles is just mixed and stirred in a pure water. Outwardly, the former has a light red color but the latter is visibly separated between nanoparticles and pure water. Pool boiling CHF experiments were performed using these nanofluids. Fig. 1 shows the results by the comparison of CHF data between magnetite-water nanofluids according to the effect of sonication with increasing the nanoparticle concentration. The CHF data without sonication represented that the CHF values were similar to the pure water case and the CHF is not improved with increasing the nanoparticle concentration. Therefore, the results show that nanofluids should be initially sonicated to guarantee the CHF enhancement of nanofluid manufactured by the two-step method.

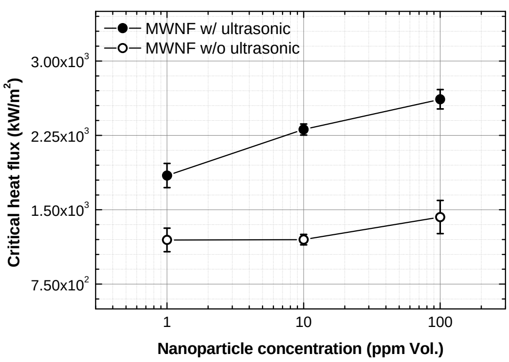

Fig. 1. Comparison of CHF data between magnetite-water nanofluids according to the manufacturing methods.

2.2 The effect of dilution

As I mentioned that it seems like nanofluids become a potential future application in nuclear power plants as a coolant in the emergency cooling system. Especially, it is expected that nanofluid could be used to enhance in-vessel retention capability in severe accident mitigation strategy due to high CHF margin of nanofluids.

However, it is not available to prepare the nanofluid with a target concentration in the present system. Because the volume of flooded cavity is too big and a large amount of nanofluid is needed, it is not agree with the economics and space utilization in the real system. Accordingly, it is required to prepare the concentrated nanofluid to reduce the volume of nanofluid and the dilution process should be required to apply the nanofluid into the cavity.

However, we don't know that how CHF can be affected by the dilution process of nanofluids. The effect of dilution on CHF is still unknown and there are no researches about the effect of dilution on CHF enhancement using nanofluids.

In order to assess the effect of dilution on CHF, the various kinds of concentrated nanofluids were prepared. And, pool boiling CHF experiments were performed using diluted nanofluid at the range of 1 to 100 ppm Vol. concentrations. VNF is the volume of concentrated magnetite-water nanofluids with a range of 100 to 10000 ppm Vol. of concentrations. V_{Water} is the volume of pure water to dilute the concentrated nanofluid. And, V_{Total} is total volume of dilute nanofluid. Through the dilution process as shown as table I, the diluted magnetite-water nanofluids were prepared and then, the CHF experiments were carried out using them.

Figure 2 shows the CHF results according to the effect of dilution compared to the CHF data without the dilution. For all the cases using 1,000 ppm Vol. of concentrated nanofluids, there is no CHF difference between dilution cases and non-dilution cases even though the changes of nanoparticle volume concentrations. However, CHF tends to decrease the improvement using 10,000 ppm Vol. of concentrated nanofluids compared to the non-dilution cases.

Table I: The relationship of nanoparticle concentrations between concentrated nanoflud and diluted nanofluid

V_{NF}/ V_{Total}	Nanoparticle concentration	
	concentrated nanofluid	**diluted nanofluid**
1	1	1
	10	10
	100	100
0.01	100	1
	1000	10
	10000	100
0.001	1000	1
	10000	10

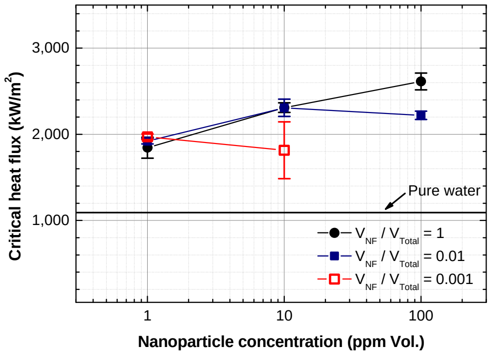

Fig. 2. CHF data between magnetite-water nanofluids according to the effect of dilution

As a result, we proved that the limitation of nanoparticle concentration was existed in the process of dilution. CHF enhancement can be guaranteed until 1,000 ppm Vol. of concentrated nanofluid without consideration of the effect of dilution in nanofluid. It is expected that the limitation of concentrated nanoparticle concentration will be used as a main criterion in the process of design. For example, the volume of the APR 1400 flooded reactor cavity is approximately 760 m^3.If the concentration of 1 ppm Vol. of nanofluid is determined as a target, the volume of stored nanofluid is almost 0.76 m^3 because the concentrated nanoparticle concentration should be limited below 1,000 ppm Vol.

2.3 The effect of storage time

In this study, two-step method was used for manufacturing the water-based nanofluids. An advantage of two-step method is that the manufacturing process is simple, cheap, and productible in bulk. However, the agglomeration of nanoparticles is not fully separated in nanofluids prepared by the two-step method. From a point of practical view, manufactured nanofluids should be conserved while keeping the excellent heat transfer. However, nanoparticles would be agglomerated after manufacturing the nanofluids using two-step method.

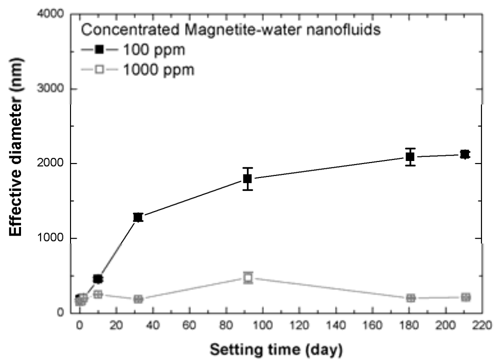

Fig. 3. Time-dependent DLS data with concentrated magnetite-water nanofluid

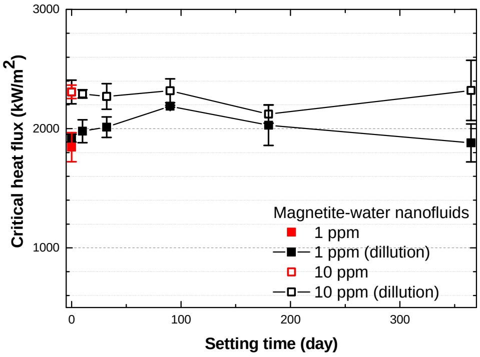

Fig. 4. Time-dependent CHF data between 1 and 10 ppm Vol. of magnetite-water nanofluids considering the effect of dilution.

In a field of heat transfer using nanofluids, generally, the poor dispersion quality causes the lowering performance of thermal heat transfer. Considering the dispersion stability of nanofluids, the thermal conductivity of nanofluids, which is the mechanism of single-phase heat transfer and related on Brownian motion, was investigated experimentally and theoretically in many research groups. However, it is not easy to find the study on the relationship between dispersion stability and CHF, which is the mechanism of two-phase heat transfer and related on the changes of surface characteristic. To evaluate the effect of storage time on CHF, 100 and 1000 ppm Vol. of concentrated magnetite-water nanofluid were prepared using two-step method. To assess the dispersion stability quantitatively, the size of nanoparticles were measured by using dynamic light scattering (DLS).

Fig. 3 shows the DLS data including the effective diameter of magnetite nanoparticles according to the setting time in 180 days. The results of 100 ppm Vol. of magnetite-water nanofluid represent agglomeration of nanoparticles was initially in rapid progress and, after 1 month, the progress of agglomeration was saturated with approximately 2,000 nm of nanoparticle size. For 1000 ppm Vol. of magnetite-water nanofluid, it is difficult to conclude the dispersion stability by measuring the DLS data, because of the opaque of magnetite-water nanofluid. Pool boiling CHF experiments were also performed using 1 and 10 ppm Vol. of diluted nanofluids which is diluted with the 100 and 1000 ppm Vol. of concentrated nanofluids, respectively. Time-dependent CHF data for magnetite-water nanofluid were plotted in fig. 4, according to the nanoparticle concentration. From this, there is no decrease in CHF values for 1 and 10 ppm Vol. of nanofluids with increasing the preserved time compared with the original CHF values. Based on these, we knew that the dispersion stability of nanoparticles in the nanofluid can't affect the CHF enhancement, exclusively. The CHF enhancement using the nanofluid made by two-step method can be guaranteed for a year at least. And, we also proved that there is no effect of dilution on CHF enhancement within the limitation of dilution ratio though the consideration of time-dependent stability.

3. Conclusions

The conclusions are summarized as below;

(1) Nanofluids, which are made by the two-step method, should be initially sonicated to guarantee the CHF enhancement of nanofluids.

(2) The limitation of nanoparticle concentration was existed in the process of dilution to keep the CHF improvement. CHF enhancement can be guaranteed until 1,000 ppm Vol. of concentrated nanofluid without consideration of the effect of dilution in nanofluids. It is expected that the limitation of concentrated nanoparticle concentration will be used as a main criterion in the process of design.

(3) The dispersion stability of nanoparticles in the nanofluid can't affect the CHF enhancement, exclusively. The CHF enhancement using the nanofluid made by two-step method can be guaranteed for a 6 months at least. And, we also proved that there is no effect of dilution on CHF enhancement within the limitation of dilution ratio though the consideration of time-dependent stability.

Based on the results, we expected that these can be based and moved a step forward to apply the nanofluid in real system of nuclear power plants considering the nanofluid stability.

REFERENCES

[1] H. Kim, J. Kim and M. Kim "Experimental study on CHF characteristics of water-TiO_2 nano-fluids," *Nuclear Engineering and Technology*, 38 (1), pp. 61-68, 2006.

[2] I. C. Bang and S. Heung Chang "Boiling heat transfer performance and phenomena of Al2O3–water nano-fluids from a plain surface in a pool," *International Journal of Heat and Mass Transfer*, 48 (12), pp. 2407-2419, 2005.

[3] S. M. You, J. H. Kim and K. H. Kim "Effect of nanoparticles on critical heat flux of water in pool boiling heat transfer," *Applied Physics Letters*, 83 (16), pp. 3374-3376, 2003.

[4] J.H. Lee. T. Lee and Y.H. Jeong "Experimental study on the pool boiling CHF enhancement using magnetite-water nanofluids," *International Journal of Heat and Mass Transfer*, 55, pp 2656-2663, 2012.

[5] J.H. Lee. T. Lee and Y.H. Jeong "The effect of pressure on the critical heat flux in water-based nanofluids containing Al2O3 and Fe3O4 nanoparticles," *International Journal of Heat and Mass Transfer*, 61, pp 432-438, 2013.