

FLOW BOILING CRITICAL HEAT FLUX ENHANCEMENT BY USING MAGNETIC NANOFLUIDS AND EXTERNAL MAGNETIC FIELDS

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Abstract

By using the nanofluid as a working fluid, we can expect the enhancement in the flow boiling critical heat flux mainly due to the deposition of nanoparticles on the heat transfer surface. In this study, we suggest the magnetic nanofluid, or magnetite-water nanofluid, as a working fluid which is regarded as a controllable nanofluid, that is, nanoparticles or magnetite nanoparticles in a nanofluid can be controlled by an external magnetic field. Therefore, we can expect the advantages of magnetic nanofluid such as, i) control of nanofluid concentration to maintain nanoparticle suspension and to localize nanofluid concentration, and ii) removal of nanoparticle from nanofluid when we want. In this study, we focused on the investigation of flow boiling critical heat flux characteristics for the magnetic nanofluid. Series of experiments were performed under the low pressure and low flow conditions, and based on the experimental results; we can conclude that the use of magnetic nanofluid improves the flow boiling critical heat flux characteristics. This is mainly due to the deposition of magnetite nanoparticles on the heat transfer surface, which results in the improvement of wettability and re-wetting characteristics of heat transfer surface. Preliminary results of the magnetic field effects on the flow boiling critical heat flux would be presented also.

Introduction

There are many engineering applications, which use a working fluid – in either flowing or stagnant state – to transport the heat or energy from one side to the other side, and the improvement of heat transfer performance has been one of the key issues for a long time. One of the cheap and easy ways to achieve the goal is the use of another working fluid having better thermal-hydraulic characteristics. In that sense, low concentration nanofluid is regarded as a good candidate for the new working fluid. The term nanofluid refers to a fluid in which nanoparticles are suspended. Since the thermal conductivity of nanoparticles is typically order-of-magnitude higher than that of base fluid, the thermal conductivity of nanofluid is relatively higher than that of base fluid. And this relatively higher thermal conductivity of nanofluid results in the improvement of heat transfer performance and overall system efficiency of engineering applications.

In the nuclear power applications, boiling heat transfer phenomena plays a key role for the efficient energy transportation during the normal operation and the successful decay heat removal at the accident situation, due to the latent heat and bubble-driven convection/turbulence. In specific, to prevent the core melt down and to mitigate the leakage of radioactivity to the outside of reactor vessel, successful removal of decay heat is necessary. For the boiling heat transfer phenomena, there exists the upper limit value in the heat transfer performance called as critical heat flux or CHF, when it occurs, there exists sudden decrease in the amount of heat transfer at the heat transfer surface due to the vapor film on it. For the higher safety margin and better system efficiency or

economics of nuclear power system, higher value of CHF is required, and the use of nanofluid as a working fluid is the one of promising options to improve the CHF characteristics. When nucleate boiling occurs at the heat transfer surface, base fluid of nanofluid evaporates out and the remaining nanoparticles deposits on the heater surface. These deposited nanoparticles improve the wettability characteristics of heat transfer surface, and finally, result in the rapid re-wetting of working fluid on the heat transfer surface.

Even though the nanofluid has the excellent thermal-hydraulic characteristics as a working fluid of engineering applications, there exist yet some problems to be solved for the real world applications. The first one is the control of nanofluid concentration, in both global and local manner. In globally, nanoparticle suspension in a base fluid should be maintained to prevent the agglomeration of nanoparticles. This is related to the sustainability of thermal-hydraulic performance of nanofluid as a working fluid. In locally, the local nanofluid concentration of interested region should be controlled as higher/lower as the concentration of bulk region for a certain purpose of engineering applications. The second one is the removal of nanoparticles from the nanofluid when the nanoparticles are not needed anymore, and they should be removed for the fine maintenance of other system components. If controllability of nanoparticles can be confirmed by some means, many of above problems could be solved. In that sense, we suggest the magnetic nanofluid as a working fluid for engineering applications, especially the nuclear power applications. The magnetic nanofluid is a controllable nanofluid by using the external magnetic fields applying on it – the use of magnetite nanoparticles can make it possible. In this study, we are mainly focusing on the measurement of flow boiling CHF characteristics under no magnetic field conditions.

1. Experiments

Including the tube test section, detailed descriptions of experimental apparatus are provided here. Appropriate test matrix has been designed. Most of experimental cases in designed test matrix are conducted in the manner of experimental procedure, which are explained in detail below.

1.1 Experimental Loop

A schematic of experimental loop used in this study is shown in Fig. 1. Centrifugal pump makes working fluid flow through the test section. In combination with a needle valve, centrifugal pump controls the mass flux of working fluid. Electromagnetic flow meter measures the mass flux of working fluid. Condenser and pre-heater make a balance of experimental loop. Working fluid temperatures at the inlet and outlet of test section are measured with in-stream K-type thermocouples. Working fluid pressure is estimated by measuring the difference of water level between a surge tank and overhead reservoir.

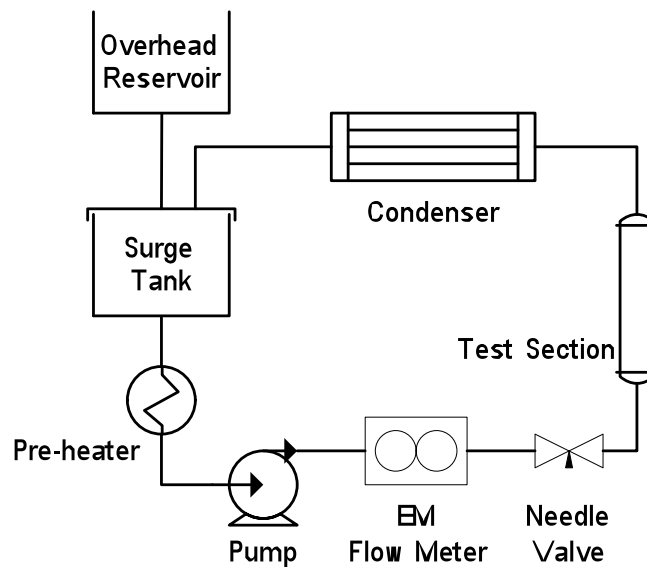


Figure 1 Schematic of flow boiling CHF test loop

1.2 Test Section

In this study, 1/2 inch SS316 tube is used as the test section for flow boiling CHF measurement experiments. A brief description of test section is tabulated in Table I. To ensure a fully-developed flow condition at the inlet of heated region, entrance length of 550.00 mm (or fifty times of tube inner diameter) is assured. The length and electrical resistance of heated region is 250.00 mm and 5.61 m-ohm, respectively.

Vertically installed test section is heated uniformly by means of direct current Joule heating with 100 kW (25V 4000A) capacity DC rectifier. Electric heating power and corresponding heat flux are estimated by measuring the electric current and potential difference values between two electrodes. Also, K-type thermocouples are attached onto the outer surface of tube test section to measure the tube wall temperature and to detect the onset of CHF.

In general, magnetic fields are generated around the electric current. Most CHF experiments use very strong electric current to heat up the heater, and, as a result, very strong magnetic field is generated near the heater surface. Therefore, it is very hard to investigate the effect of working fluid itself on the CHF characteristics.

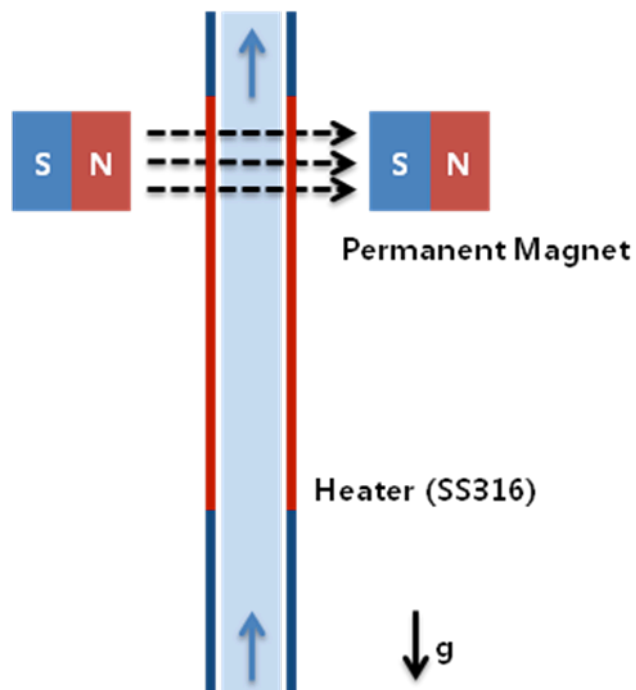


Figure 2 Tube test section – permanent Neodymium magnets installed at the end of heating surface region

However, there are no electricity-induced magnetic fields inside the tube test section. This is well-known fact and is based on the principle of symmetry. Therefore, the effect of working fluid itself and the effect of magnetic field on the CHF characteristics can be de-coupled and investigated respectively. To make a strong magnetic field inside the tube test section, permanent Neodymium magnets are used. Installation position of these permanent Neodymium magnets is just below the upper electrode, at which CHF would occur. Fig. 2.

Uniformly Heated Tube (SS316)	
Outer Diameter	12.70 mm
Inner Diameter	10.92 mm
Entrance Length	550.00 mm (L/D = 50.0)
Heated Length	250.00 mm (L/D = 22.9)
Electric Resistance	5.61 m-ohm

Table 1 Description of Test Section

1.3 Test Matrix

All experiments are conducted under low pressure and low flow (LPLF) condition, which is the accident condition of light water reactors (LWR) and normal or transient conditions of research reactors. Experimental conditions are summarized in Table II.

Working Fluid	
Nanoparticle	Fe ₃ O ₄ , Al ₂ O ₃
Concentration	0, 1, 10 ppmv
Fluid Flow Conditions (Vertical Upward Flow)	
Mass Flux	100, 300, 500 kg/m ² s
Pressure	about 1 bar
Inlet Subcooling	50 K (208.05 kJ/kg)
Magnetic Field Condition	
Intensity	0, 300 G

Table 2 Test Matrix

In this study, magnetite-water nanofluid or magnetic nanofluid (MNF) is used as a working fluid with concentration variations from 0 to 100 ppmv. (ppmv – part per million volume) Magnetic nanofluid is a colloidal suspension of magnetite (Fe₃O₄) nano-particles in DI water. Average particle size of magnetite nano-particles is 25 nm and magnetite nano-particles are dispersed in DI water by means of ultrasonic wave, which is generated by commercial ultrasonic cleaner. To certain the degree of dispersion of magnetite nano-particles in DI water, more than 6 hours are needed as ultrasonic wave dispersion time. Well-dispersed magnetic nanofluids with concentrations of 1 to 100 ppmv are shown in Fig. 2.



Figure 2 Well-dispersed magnetic nanofluids with concentrations of 1, 10 and 100 ppmv (from left to right)

Working fluid flows through the vertical tube test section in upward direction. Mass flux of working fluid flow varies from 100 to 500 kg/m²s, which are relatively low mass flux range. All experiments are conducted under about atmospheric pressure and 50 K (or 208.05 kJ/kg) inlet sub-cooling condition. Considering the hydraulic head of experimental loop, the actual local pressure of tube test section would be in the range from 1.1 to 1.2 bars.

As mentioned above, permanent Neodymium magnets are used to make the strong magnetic fields on the tube test section. In this study, the direction of magnetic fields is perpendicular to the flow direction of working fluid in the tube. The magnitude of applied magnetic fields varies from 0 to 300 gauss by using different number of permanent Neodymium magnet pairs.

1.4 Experimental Procedure

At first, the experimental loop is filled with prepared working fluid, that is, magnetic nanofluid. And then, the working fluid flows in the experimental loop for 30 minutes with relatively high mass flux of about 1,500 kg/m²s, to mix and disperse the working fluid further. After that, mass flux and inlet sub-cooling values are adjusted to the experimental conditions, and those two are maintained as constant values during the experiment – it can be done by controlling the output dials of both pump and pre-heater simultaneously. Especially, to control the low mass flux is much difficult mainly due to the existence of natural circulation – which depends on the heat flux level.

During the experiment, electric heating power and corresponding heat flux are gradually increased by controlling the output dial of DC rectifier in constant voltage mode. Since the magnetic nanofluid is used as a working fluid, the increasing history of electric heating power should be controlled for every experiment – it is related to the deposition phenomena of nano-particles on the heater surface when nucleate boiling occurs. In this study, increasing history of electric heating power is varied to investigate the kinetics of flow boiling CHF for magnetic nanofluid, with and without the existence of a strong magnetic field.

CHF onset point is detected with the observation of sudden rise in tube wall temperature. Knowing CHF onset point with electric current and potential difference values between two electrodes, CHF is calculated according to the simple equation, Eq. (1)

$$q'' = V I / \pi ID L \quad (1)$$

In Eq. (1), q'' is the heat flux value in Watt. V and I are, respectively, electric potential difference and current values between two electrodes in Volt and Ampere. ID is tube inner diameter and L is length of heated region both in meter.

2. Results and Discussion

The experimental results and discussion are followed in three parts: 1) effects of magnetic nanofluids itself on the flow boiling CHF characteristics, 2) comparison of the flow boiling CHF characteristics – magnetite-water nanofluids vs. alumina-water nanofluids and 3) effects of magnetic fields on the flow boiling CHF characteristics for magnetic nanofluids.

2.1 Effects of Magnetic Nanofluids

To investigate the effects of magnetic nanofluids itself on the flow boiling CHF characteristics, flow boiling CHF experiments are conducted under a zero-strength magnetic field condition: the results are summarized in Fig. 4.

For the case of magnetic nanofluids concentration of 0, that is, for the case of pure water, the value of flow boiling CHF is almost linearly proportional to the mass flux of working fluid. The values of exit quality are varied with the mass flux of working fluid, from 0.07 for mass flux of 500 kg/m²s to 0.31 for mass flux of 100 kg/m²s. Every case in this study corresponds to the annular flow regime, based on the Hewitt and Roberts map for vertical upflow in a tube. For annular flow regime, liquid film dryout (LFD) type CHF occurs, rather than departure from nucleate boiling (DNB) type CHF. Therefore, we can conclude that LFD type CHF occurs in all cases of this study.

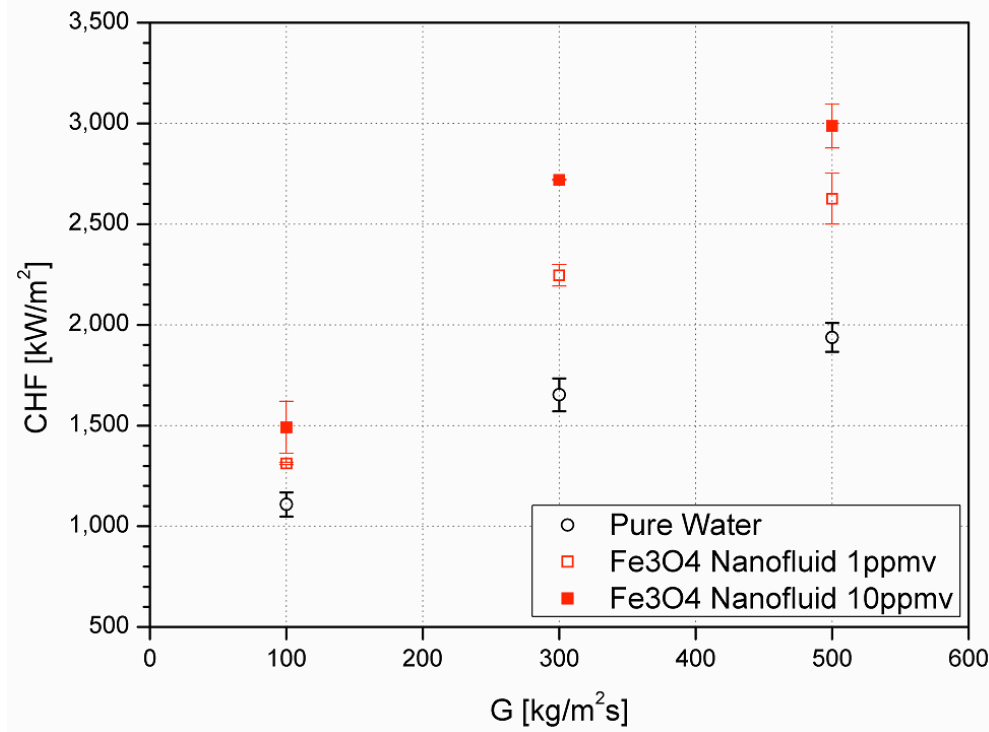


Figure 4 Effects of magnetic nanofluids itself on the flow boiling CHF characteristics

By using the magnetic nanofluids as a working fluid, the flow boiling CHF characteristics is improved drastically. The degree of flow boiling CHF enhancement is higher when the magnetic nanofluids of higher concentration are used as a working fluid.

The reasons of improvement in the flow boiling CHF characteristics for the magnetic nanofluids are summarized as followed: 1) when nucleate boiling occurs on the heater surface, magnetite nanoparticles in the magnetic nanofluids are deposited on the heater surface. And the deposition of magnetite nanoparticles results in the improvement of wettability and rewetting characteristics of heater surface. As a consequence, the flow boiling CHF characteristics is improved by using the magnetic nanofluids as a working fluid. It seems that the amount of deposited magnetite nanoparticles on the heater surface depends not only on the concentration of magnetic nanofluids but also on the amount of magnetic nanofluids evaporation on the heater surface. Therefore, the history of heater power should be controlled for the impartial comparison. 2) Compared with the pure water, magnetic nanofluids has better wettability and rewetting characteristics for the heater surface – which are made of SS316. Contact angle measurement result supports this statement.

In summary, the use of magnetic nanofluids itself improves the flow boiling CHF characteristics drastically, and this promising result comes from the improvement in the wettability and rewetting characteristics of both a working fluid and the heater surface. As a further work, we should explain the reason of flow boiling CHF enhancement in detail, by considering the mechanism of LFD-type CHF occurrence.

2.2 Comparison to the Alumina-Water Nanofluids

The mechanism of flow boiling CHF enhancement for magnetic nanofluids, described in section 2.1, is very similar with that for alumina-water nanofluids. The only difference between those is a

raw material of nanoparticles – magnetite (Fe_3O_4) for magnetic nanofluids and alumina (Al_2O_3) for alumina-water nanofluids. In this study, the comparison of flow boiling CHF characteristics between magnetic nanofluids and alumina-water nanofluids is given based on the experimental results, shown in Fig. 5a and Fig. 5b.

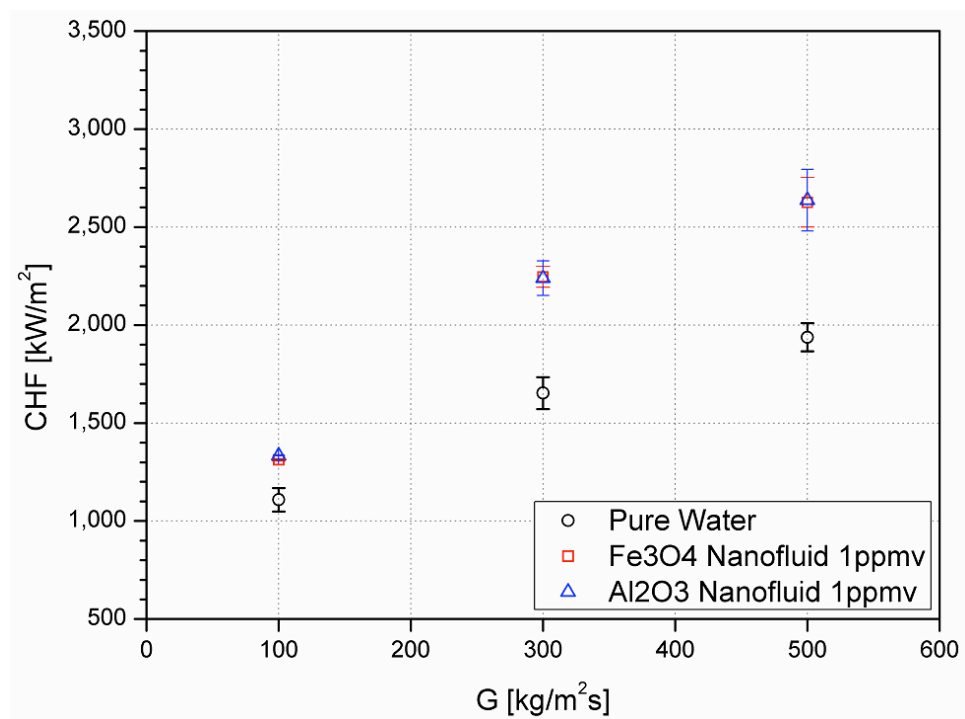


Figure 5a Comparison of the flow boiling CHF characteristics: magnetite-water nanofluids vs. alumina-water nanofluids with concentration of 1ppmv

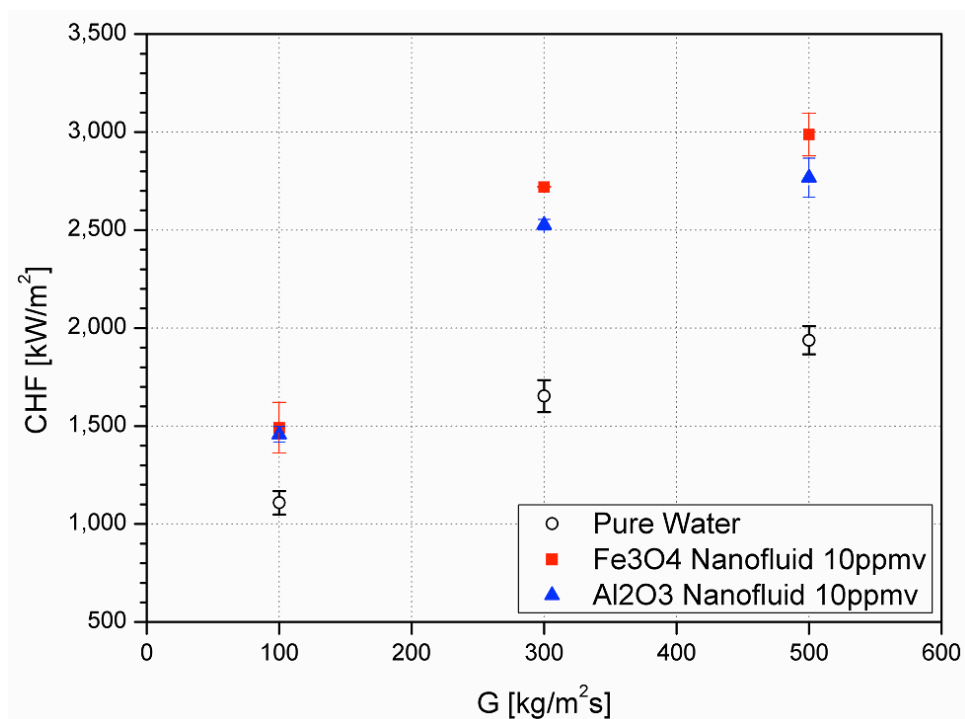


Figure 5b Comparison of the flow boiling CHF characteristics: magnetite-water nanofluids vs. alumina-water nanofluids with concentration of 10ppmv

In fact, there is no difference in the flow boiling CHF values between two nanofluids – magnetic nanofluids and alumina-water nanofluids – with concentration of 1ppmv. However, as you can see in Fig. 5b, the flow boiling CHF values of magnetic nanofluids are slightly higher than those of alumina-water nanofluids, when the concentration of two nanofluids is 10ppmv. Therefore, we can conclude that a magnetic nanofluid is better than alumina-water nanofluids, in terms of boiling heat transfer capability on the heater surface. As a further work, we should explain the reason of difference in the boiling heat transfer capability between two nanofluids – magnetic nanofluids and alumina-water nanofluids.

2.3 Effects of Magnetic Fields

To investigate the effects of external magnetic fields on the flow boiling CHF characteristics for magnetic nanofluids, a series of flow boiling CHF experiments were conducted under external magnetic fields condition: about 300 gauss. The results are summarized in Fig. 6a and Fig. 6b.

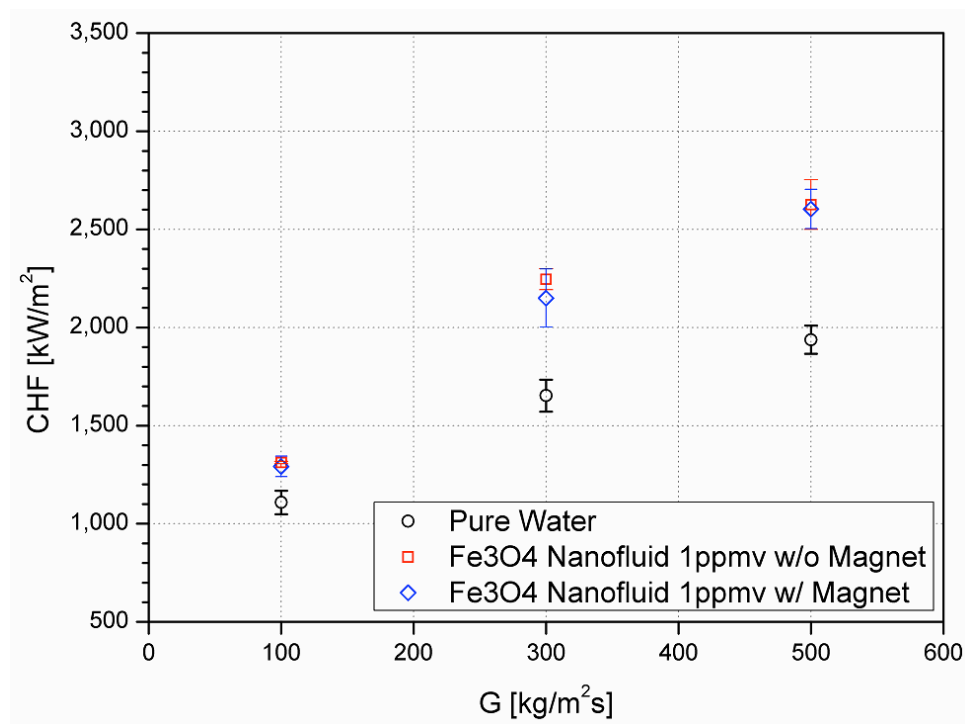


Figure 6a Effects of magnetic fields on the flow boiling CHF characteristics for magnetic nanofluids with concentration of 1ppmv

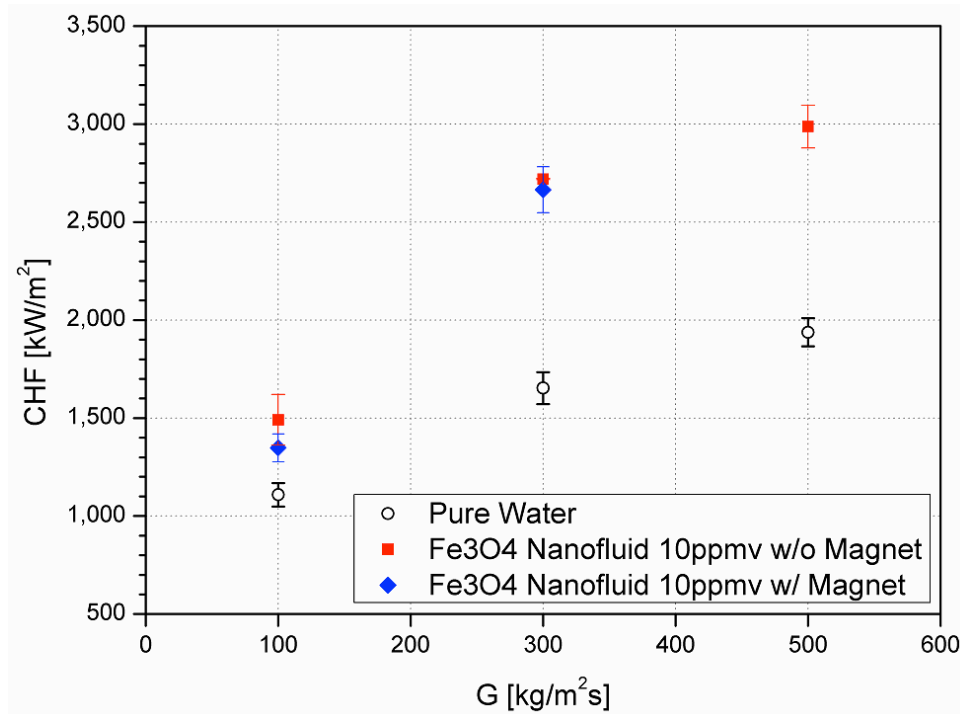


Figure 6b Effects of magnetic fields on the flow boiling CHF characteristics for magnetic nanofluids with concentration of 10ppmv

For magnetic nanofluids with concentrations of both 1 and 10ppmv, the effects of magnetic fields are negative in terms of flow boiling CHF characteristics. This pessimistic result comes from the suppression of bubble mobility in very near heater surface region, where the concentration of magnetic nanofluids is very high due to the existence of the very strong external magnetic fields of 300G. Compared with the pure water case, however, the flow boiling CHF characteristics for magnetic nanofluids are improved drastically, whether the very strong external magnetic fields exists or not.

3. Conclusions

Flow boiling CHF experiments were performed for magnetite-water nanofluids or magnetic nanofluids of various concentrations with and without the strong external magnetic fields. The enhancement in the flow boiling CHF values exists for magnetic nanofluids with respect to that of pure water cases, whether the strong external magnetic fields exist or not. As the further work, kinetics of flow boiling CHF characteristics should be examined, with and without the external magnetic fields.

4. Acknowledgements

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