Effects of Magnetic Field on Flow Boiling CHF in Fe_3O_4 Ferrofluid

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1. Introduction

Boiling heat transfer is very efficient heat transfer method due to the existence of latent heat and bubble-driven convection or turbulence. Therefore, there exist many applications, such as power plants or microscopic heat transfer devices, which use boiling heat transfer method. But the performance of boiling heat transfer phenomena has upper limit, called as critical heat flux (CHF), and the enhancement of CHF has been a key issues for a long times. In specific, CHF is strongly related to the safety problem of nuclear power plant, such as light or heavy water reactors. Therefore, many nuclear engineers have researched this topic.

To improve the CHF characteristics, many attempts have been tried, and using nanofluid as working fluid is regarded as a one promising candidate in this research area. By using nanofluid as working fluid, the CHF characteristics are improved drastically. The main reason of CHF enhancement would be the incensement in wettability of heater surface due to the deposition of nanoparticles on heater surface.

In this paper, Fe_3O_4 ferrofluid is used as working fluid. Since ferrofluid has higher thermal conductivity with respect to the nanofluid, and the existence of external strong magnetic field helps the deposition of Fe_3O_4 particles on heater surface, more improvement would be expected in the CHF characteristics. To prove these hypotheses, series of experiments are conducted.

2. CHF Experiments using Fe_3O_4 Ferrofluid

2.1 Experimental Apparatus and Test Matrix

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 upward direction. 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.

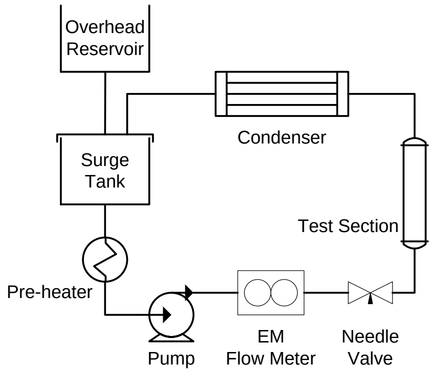

Fig. 1. Schematic of flow boiling CHF test loop

In this study, SS316 tube is used as a test section. A brief description of test section is tabulated in Table I. Test section is installed vertically and heated uniformly by Joule heating with 100kW (25V 4000A) capacity DC rectifier. Heating power for test section is estimated by measuring the electric current and potential difference between two electrodes. K-type thermocouples are attached onto the outer surface of tube to measure the tube wall temperature and to detect the onset of CHF.

Table I: Description of Test Section

Uniformly Heated Tube (SS316)	
Outer Diameter	12.70 mm
Inner Diameter	10.92 mm
Heated Length	500.00 mm (L/D = 45.8)
Entrance Length	550.00 mm
Electric Resistance	11.21 mohm

Inside the test section, there are no electricity induced magnetic fields. Therefore, the effects of working fluid and magnetic field can be investigated respectively. To make a strong magnetic field inside the test section, 1250 G permanent magnet is used. Installation position of this permanent magnet is just below the upper electrode, at which CHF would occur.

All experiments are conducted under low pressure and low flow (LPLF) conditions, which is the accident conditions of light water reactors (LWR) and normal or transient conditions of research reactors. Experimental conditions are summarized in Table II. Two different working fluids – DI water and Fe_3O_4 ferrofluid based on DI water – are used with concentration variations from 0 to 10 ppmv. Mass flux of working fluids varies from 100 to 300 kg/m^2s. All experiments are conducted under about atmospheric pressure condition.

Temperature at the test section inlet is about 273 + 50 K, that is, inlet sub-cooling of 208.05 kJ/kg condition.

Table II: Test Matrix

Working Fluid (DI Water + Fe_3O_4 Ferrofluid)	
Concentration	0, 1, 10 ppmv
Fluid Flow Conditions	
Mass Flux	100, 200, 300 kg/m^2s
Pressure	101.3 kPa
Inlet Temperature	273 + 50 K (208.05 kJ/kg)
Magnetic Field Condition	
Intensity	0, 1250 G

2.2 Results and Discussion

For DI water cases, CHF is linearly proportional to the mass flux (Fig. 2) and the exit quality ranges from 0.29 to 0.31. Based on the Hewitt and Roberts map for vertical upflow in a tube, flow patterns of every case in this study correspond to the annular flow regime. For annular flow regime, liquid film dryout (LFD) type CHF occurs rather than departure from nuclear boiling (DNB) type CHF. Therefore, we can conclude that LFD type CHF occurs in all experiments of this study.

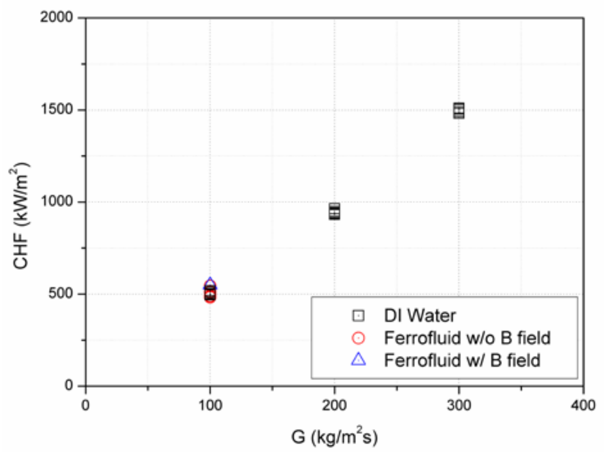

Fig. 2 CHF as a function of mass flux for water and for Fe_3O_4 ferrofluids with and without magnetic field

For mass flux of 100 kg/m^2s cases, there exists a marginal increment – actually no enhancement – in CHF values when ferrofluid is used as a working fluid with or without external strong magnetic field. (Fig. 3) This is due to the type of CHF mechanism. As mentioned above, LFD type CHF occurs in the cases of this study. In LFD type CHF, heater surface condition does not affect the CHF characteristics at all. In LFD type CHF, All heater surfaces are covered by thin liquid film, and there are no chances for heater surface condition to play an important role in CHF occurrence. Furthermore, the amount of Fe_3O_4 particles deposited on heater surface would be much smaller than DNB type CHF cases. Particle deposition phenomena occurs when bubble is generated and departed from heater surface, but in LFD type CHF, there are much smaller bubble generation at the heater surface compared with DNB type CHF.

In summary, LFD type CHF occurs in this study's experiments, therefore, there is no actual enhancement in CHF when using ferrofluid as a working fluid with or without external strong magnetic field.

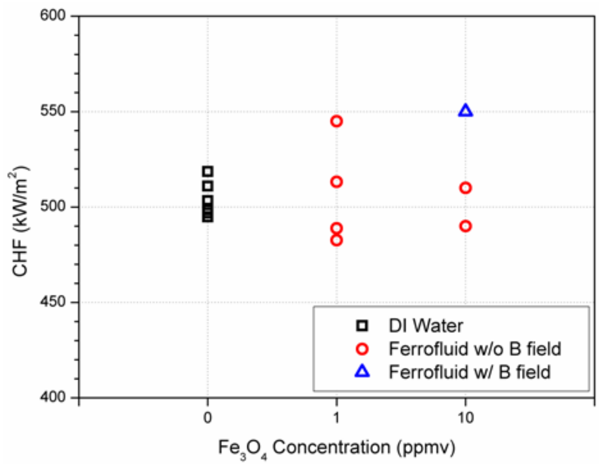

Fig. 3 CHF with respect to the Fe_3O_4 concentration for mass flux of 100 kg/m^2s

As a further work, more CHF experiments would be performed for other flow pattern, such as bubbly flow regime. In bubbly flow regime, DNB type CHF would occurs and therefore, we could expect the enhancement of CHF values when ferrofluid is used as a working fluid, with or without external strong magnetic field

3. Conclusion

Flow boiling CHF experiments were performed for Fe_3O_4 ferrofluid with and without external strong magnetic field. But there were marginal enhancement in CHF when Fe_3O_4 ferrofluid is used as a working fluid. More experiments should be performed for other flow pattern, such as bubbly flow regime

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