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Experimental Study on the Effect of Magnetic Field on Critical Heat Flux of Ferrofluid Flow Boiling in a Vertical Tube

A. Qhafuri[*]
M.Sc. Student

H. Aminfar[†]
Professor

M. Mohammadpourfard[‡]
Associate Professor

R. Maroofiazar[§]
Assistance Professor

In the present work, the critical heat flux measurements were performed for the subcooled flow boiling of pure water and magnetic nanofluids (i.e., water + 0.01 and 0.1 vol.% Fe_3O_4) in a vertical tube. The effect of applying an external magnetic field on the CHF variation was studied experimentally as well. The obtained results indicated that the subcooled flow boiling CHF in the vertical tube is increased by using the nanofluid as the working fluid, especially in lower volume concentration of nanoparticles. The nanoparticles deposition on the tube inner surface and consequently improvement of the surface characteristics such as nucleation site density, wettability and re-wetting properties could be mentioned as the main reasons of this incident. Moreover, it was seen that applying the magnetic field leads to the additional enhancement in the CHF of ferrofluids. It could be clarified as the attraction of the nanoparticles into the magnets and increasing the surface wettability resulted in the CHF enhancement.

Keywords: Subcooled Flow Boiling, Vertical tube, Magnetic Field, Ferrofluid, Critical Heat Flux.

1 Introduction

Boiling is an efficient mechanism for high heat removal of industrial systems such as steam generators, nuclear reactors, etc. The main limiting condition for the safe operation of boiling systems is critical heat flux (CHF) which is an important parameter in pool and flow boiling process. Many studies have been performed on flow boiling in tubes applying high flow and high pressure conditions [1–5]. CHF at low flow and low pressure is also very important due to the accident conditions of boiling water reactors.

One of the common ways for improving the heat transfer characteristics is using the nanofluid as a working fluid. Nanofluids are colloidal suspensions engineered by dispersing nano-sized particles into the traditional heat transfer fluids such as water and refrigerants.

[*] M.Sc. Student, Faculty of Mechanical Engineering, University of Tabriz, Tabriz, Iran, amirqhafuri@ymail.com
[†] Professor, Faculty of Mechanical Engineering, University of Tabriz, Tabriz, Iran, hh_aminfar@tabrizu.ac.ir
[‡] Corresponding Author, Associate Professor, Faculty of Chemical and Petroleum Engineering, University of Tabriz, Tabriz, Iran, Mohammadpour@tabrizu.ac.ir
[§] Assistance Professor, Department of Mechanical Engineering, Faculty of Mechanical Engineering, University of Maragheh, Maragheh, Iran, Maroofiazar@maragheh.ac.ir

One of the special types of nanofluids is the magnetic fluids, also called ferrofluids, which is synthesized using colloidal mixtures of non-magnetic carrier liquid containing magnetized nanoparticles. The ferrofluids behave as a fluid that is affected by an external magnetic field and it is applicable in various fields such as electronic packing, mechanical engineering, thermal engineering, aerospace and bioengineering [12–15].

In the case of boiling heat transfer, there have been significant amount of researches on the effect of nanofluids on pool boiling. On the other hand, research in convective flow boiling of nanofluids become more popular in the recent years. Critical heat flux (CHF) is one of the important parameters considered in previous studies. Kim et al. [16] studied the flow boiling of water based alumina, zinc oxide and diamond nanofluids experimentally. Their results indicated that CHF values of nanofluids enhanced up to 40-50% with respect to pure water. Kim et al. [17] have conducted CHF experiments at low flow and low pressure in vertical tube using Al_2O_3 nanofluids. The results showed the nanofluids CHF increase up to 70% in flow boiling for all experimental conditions. Ahn et al. [18, 19] investigated the effect of nanofluid in flow boiling on a short heated surface experimentally. Their obtained results illustrated that the nanofluid flow boiling CHF enhancement by the forced convective flow was more remarkable compared to the pure water. There have been a few studies on the effect of magnetic fields on the nanofluid flow boiling. One of the earliest and most important ones has been conducted by Kamiyama and Ishimoto [20]. In their study, the effects of the magnetic field on characteristics of the boiling two-phase pipe flow of a magnetic fluid have been investigated both theoretically and experimentally. The utilized fluid in this study was a hexane-based magnetic fluid with manganese-zinc ferrite particles of 50% weight concentration. The aspect of boiling two-phase flow was visualized with ultrasonic wave echo in the region of non-uniform magnetic field and various distributions of two-phase flow characteristics were obtained. The results revealed that precise control and stabilization of boiling flow of a magnetic fluid are possible using the magnetic force of the fluid effectively. The other remarkable result of this study was the void fraction reduction in a strong magnetic field.

Recently, Lee et al. [21] has performed a series of experiments at the atmospheric pressure and low mass flow conditions on the CHF of magnetic nanofluid. Based on their experimental data, it was concluded that the use of magnetic nanofluid improves the flow boiling CHF characteristics, i.e., the flow boiling CHF is enhanced for the magnetic nanofluid. Moreover, the effects of magnetic field on the flow boiling CHF for the magnetic nanofluid were investigated and the results indicated an additional improvement in flow boiling CHF. According to their statement, the permanent magnets attracted the magnetic nanoparticles and local concentration of the nanofluid near the tube wall became higher compared to the bulk region, and therefore the higher flow boiling CHF was measured.

The novelty of the present work is to investigate the magnetic field effect on the subcooled flow boiling of a magnetic nanofluid flowing inside a vertical tube experimentally. Furthermore, the effects of the addition of magnetic nanoparticles on the basefluid inside a tube on the critical heat flux will be studied experimentally and the influence of applying magnetic field on the CHF values of the boiling ferrofluid flow will be investigated.

2 Test Procedure

2.1 Nanofluid Preparation

In current study, Ferrofluids have been prepared by dispersing 0.01 and 0.1 vol.% of Fe_3O_4 nanoparticles into the water as a base fluid. Properties of the utilized nanoparticles have been summarized in Table (1).

Table 1 Properties of Fe_3O_4 nanoparticles

Purity	99.5+%
APS	15-20 nm
BET	81.98 m^2/g
Morphology	Spherical
Bulk density	~ 0.85 g/cm^3
True density	4.8-5.1 g/cm^3

The process of preparation of ferrofluids is started by weighting the mass of Fe_3O_4 nanoparticles t with a digital electronic balance and then adding the nanoparticles into the weighed water. Next, the mixture was sonicated continuously for three hours with a sonicator of the bath type to obtain a uniform dispersion of Fe_3O_4 nanoparticles in the water. In the meanwhile, the temperature of ferrofluids has been increased from 20 to 60 °C.

2.2 Experimental setup

The experimental loop was constructed in order to measure CHF values for water and ferrofluids flow boiling under conditions of low pressure and low flow (LPLF conditions).
A schematic diagram of the experimental loop is shown in Figure (1). The loop consist of the test section, preheater, heat exchanger, centrifugal pump, and a turbine flow meter.

The test section in this study is a stainless steel 304 vertical tube which its inner diameter, outer diameter and heated length are 6 mm, 8 mm and 72 cm, respectively. A summary of the experimental range of parameters in current study is given in Table (2). Cooper electrodes were attached to both ends of the tube to connect a 24kW DC power supply (30V and 800A). The Electrical heating power and the corresponding heat flux are calculated by measuring the electric current and the electric potential difference between two electrodes as follows:

$$q_c = \frac{V.I}{\pi D_i L} \quad (1)$$

Where V and I are the measured potential difference between two electrodes and electric current, respectively. D_i is the inner diameter and L is the heated length of the tube. To detect the onset of CHF, K-type thermocouples are attached and fixed to the outer surface of the tube (see Figure 2).

Figure 1 Working fluids (a) pure water, (b) 0.01 vol.%, and (c) 0.1 vol.% ferrofluid.

Table 2 Experimental range of parameters

Pressure	85 kPa
Mass flux	0-300 kg/m2.s
Inlet subcooling	25 K (106 kj/kg)
Nanoparticles volume fraction	0, 0.01, 0.1 %
D_i	6 mm
D_o	8 mm
Heated length	0.72 m
Magnetic field intensity	0, 150 mT

To make a strong external magnetic field inside the annulus, permanent magnets are used. The magnets are located in a way that the quadrupole magnet is formed. The quadrupole magnets consist of groups of four magnets and are useful as they create a magnetic field in which the magnitude grows rapidly with the radial distance from its longitudinal axis. The installation position of the magnet pairs is below the upper electrode, where the CHF would occur. The installed quadrupole magnet and its magnetic field lines are illustrated in Figure (2).

2.3 Experimental procedure

The CHF measurements have been performed by the following procedures. The loop is filled with the working fluid (water or ferrofluids) and in the case of ferrofluids, the working fluid flows through the experimental loop for 30 min with a relatively high mass flux to provide a homogenous suspension of the nanoparticles. Then, the fluid is degassed by boiling in the warm up period of the experiments (about half an hour).

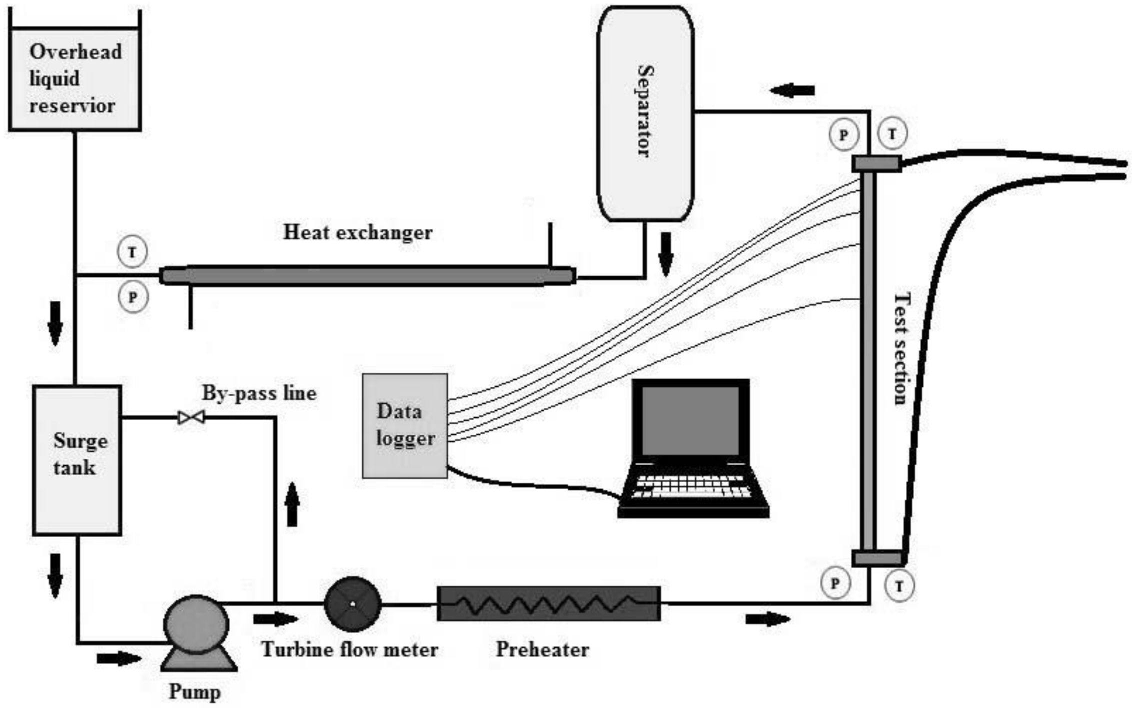
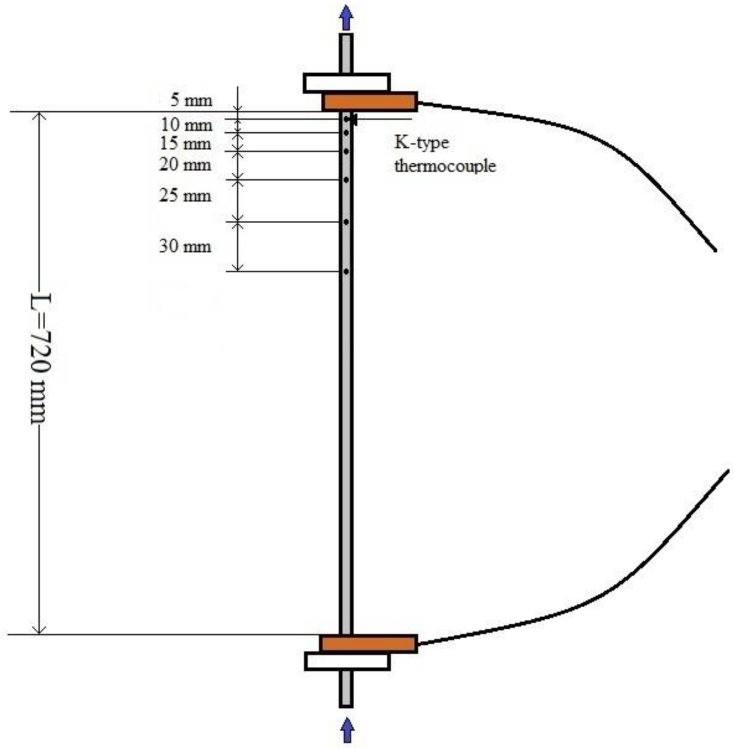


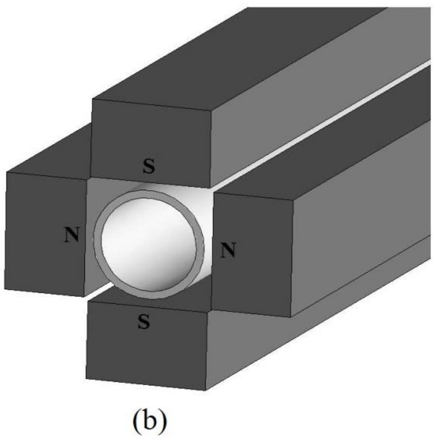
Figure 2 Schematic diagram of experimental loop.

The fluid which is discharged from the test section is entered in the designed heat exchanger; it is condensed and cooled to 20°C and returned to the main tank, again. The water is preheated by the pre-heater to get the desired inlet subcooling condition. The fluids flow rate is adjusted by speed control of the pump. After setting the fluid flow rate and inlet subcooling at the desired values, the electric power is increased gradually.

At each power level, the measured parameters are allowed to stabilize for several minutes to achieve a steady-state condition before further raising. This process continues until a sharp increase of the wall temperature is observed on the tube surface. A CHF condition is determined to occur when one of the wall temperatures of the tube shows a continuous sharp increase and then reaches 250°C. Whenever the CHF occurs, the electric current is automatically or manually stopped to prevent any damage to the tubes. The variations of the temperatures of the thermocouples at the moment of the occurrence of the CHF are shown in Figure (3).



(a)



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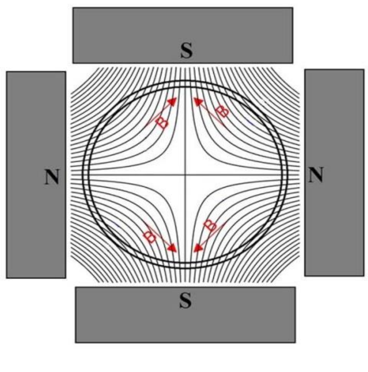

(c)

Figure 3 (a) Test section and thermocouple locations; (b) used quadrupole magnet; and (c) magnetic field lines.

It should be mentioned that in each case studies, the used tube is replaced with the new one to prevent the changed surface characteristics influence on the next experiment results.
Different measurement devices were installed in the test loop in order to control the system state and to determine the relevant experimental parameters. The mass flow was measured with a turbine flow meter, fluid temperature and pressure were determined with K-type thermocouples and Omega PXM209 (0–6 bar) absolute pressure transducers, respectively. The relevant devices were calibrated to determine the measurement accuracies.
An uncertainty analysis is done on the experimental results. The uncertainty of a parameter which is a function of several variables depends on the uncertainties of those variables.

The overall uncertainty of the measurement result y obtained from:

$$u_y^2 = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) \quad (2)$$

The maximum values for the uncertainty for tube diameter, mass flux and heat flux are ±0.01mm, 4% and 4% respectively.

3 Results and discussion

Figure (4) shows a comparison between pure water and ferrofluids CHF values. As it is shown, dispersing nanoparticles in the base fluid increase the CHF values and this enhancement have been improved by increasing the volume fraction of the nanoparticles. The noticeable point is that the difference between the CHF values of the pure fluid and nanofluids is more significant at higher mass flow rates. The maximum increase of CHF was 19% and 32% for 0.01 and 0.1 vol.% of ferrofluids, respectively.

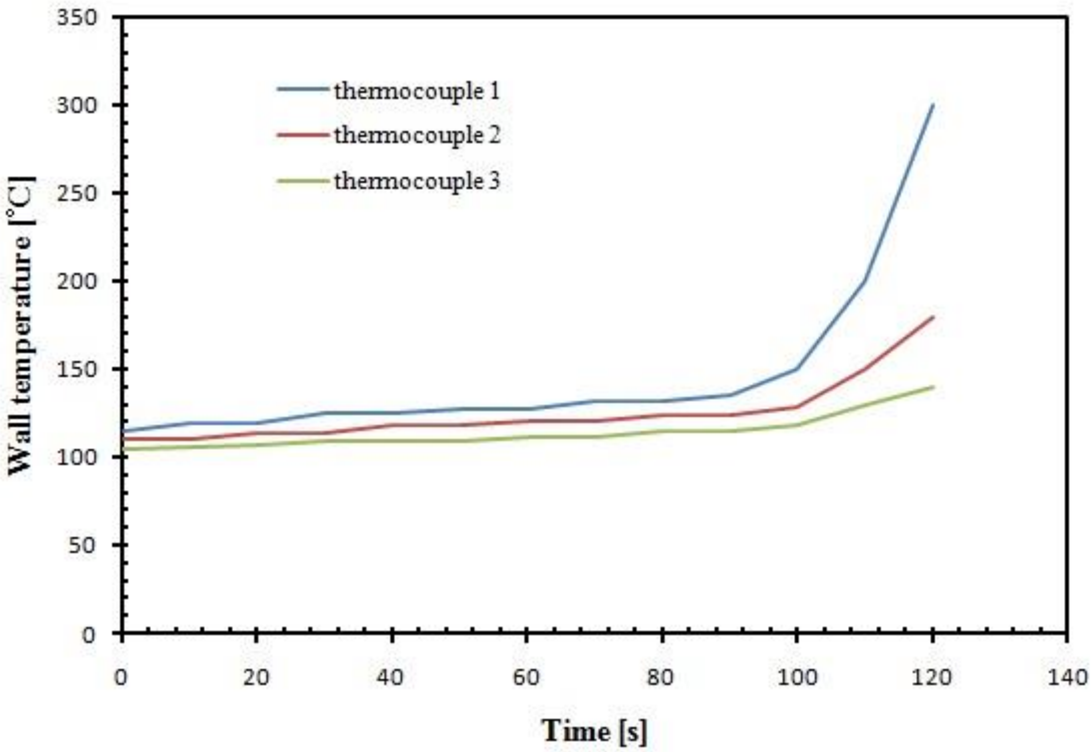

Figure 4 Wall temperature recorded by data logger

The main recognized reason for the CHF enhancement of the nanofluids could be the nanoparticles deposition over the heated surface and occurrence of variations on the surface characteristics such as the number of nucleation sites density and wettability of the boiling surface [16-19]. To investigate this issue, the SEM images of the heated surface where the CHF has been occurred are shown in Figure (5). Figures (5-a) and (5-b) show the tube surfaces before and after boiling experiments with pure water. As it is seen, the surface characteristics have been changed after the CHF test for the pure water. Figures (5-c) and (5-d) illustrate the SEM images of the surface of the tube after boiling of 0.01% and 0.1% volume fraction ferrofluids, respectively. It is evident from these figures that the deposition of nanoparticles has been occurred in both cases and as it was expected, the deposition is superior for the higher volume concentration of nanoparticles.

With respect to the obtained results shown in Figs. (4) and (5), it seems that increase in deposition of nanoparticles may lead to extra enhancement of CHF. To intensify this phenomenon, an external magnetic fie is employed to attract the nanoparticles on the tube inner surface. This step could improve the nanoparticles deposition. For this purpose, quadrupole magnet is used to create the external magnetic field. The boiling procedures have been repeated and the effects of magnetic field utilization on CHF values have been shown in Figures (6) and (7). As shown, for the ferrofluids with lower nanoparticle concentration (see Figure 6), there is a significant difference between CHF values before and after the external magnetic field implementation. The maximum enhancement of CHF in this case is about 30% for zero flow condition and 17% for flow boiling condition.

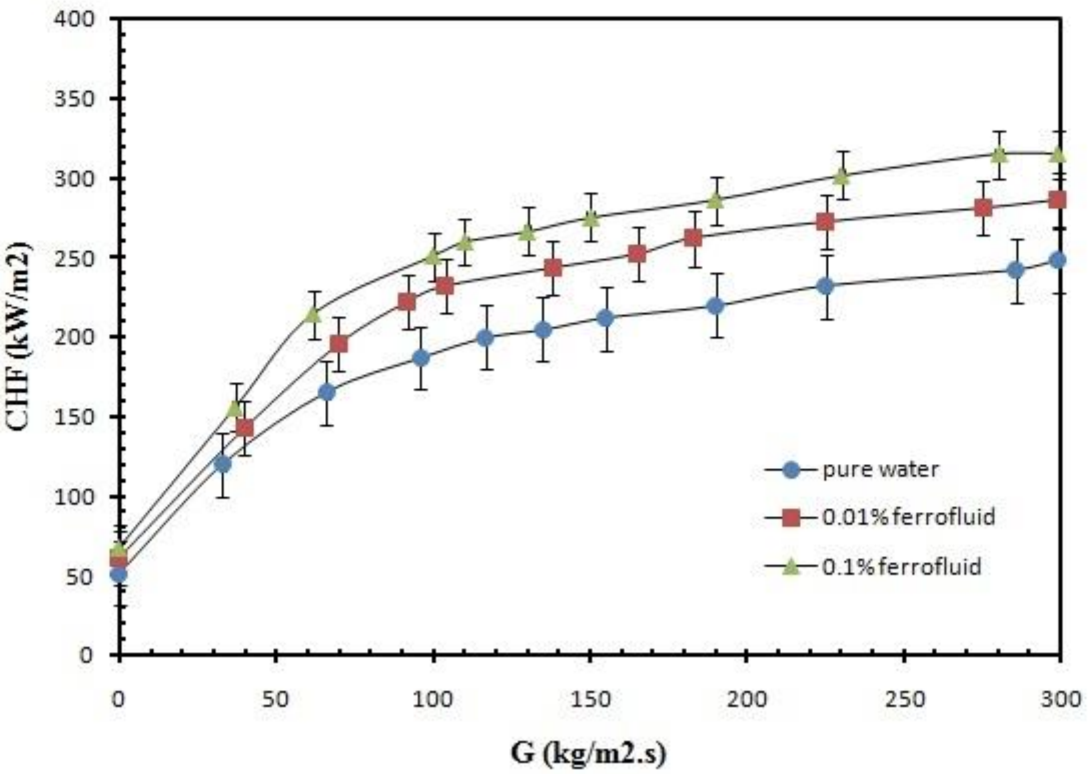

Figure 5 Comparison of pure water and ferrofluids CHF.

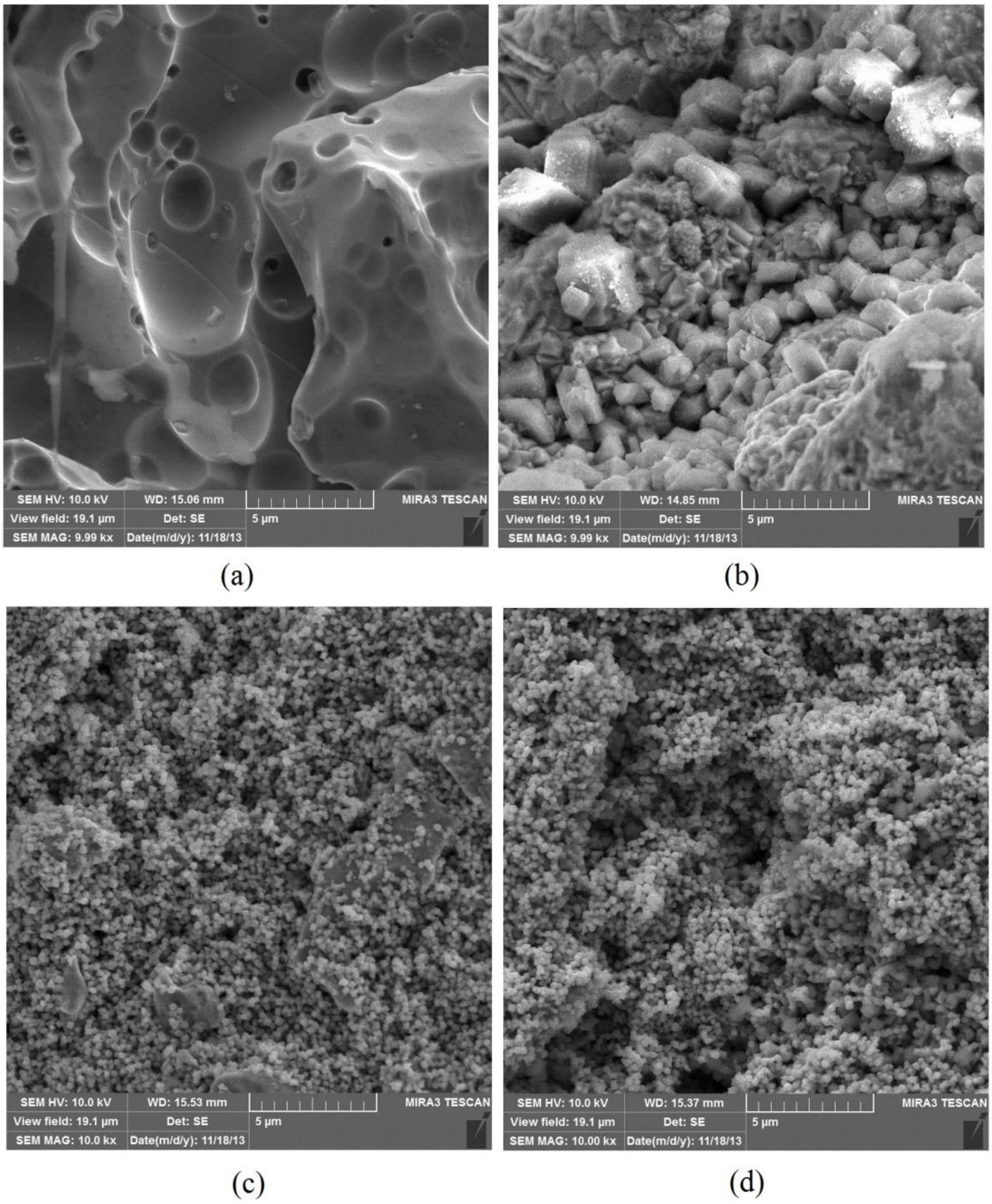

Figure 6 SEM image of tube inner surface; (a) as-received tube, (b) after boiling of pure water, (c) after boiling of 0.01 vol.% ferrofluid, and (d) after boiling of 0.1 vol.% ferrofluid.

On the other hand, for higher volume fraction of nanoparticles, the CHF is also increased by applying the magnetic field (see Figure 7), but the CHF enhancement in comparison to the case with volume fraction of 0.01% ferrofluid is lower. In this case, the maximum CHF increase is about 10% for zero and flow boiling conditions. This phenomenon can be appeared due to the nanoparticles deposition saturation condition.

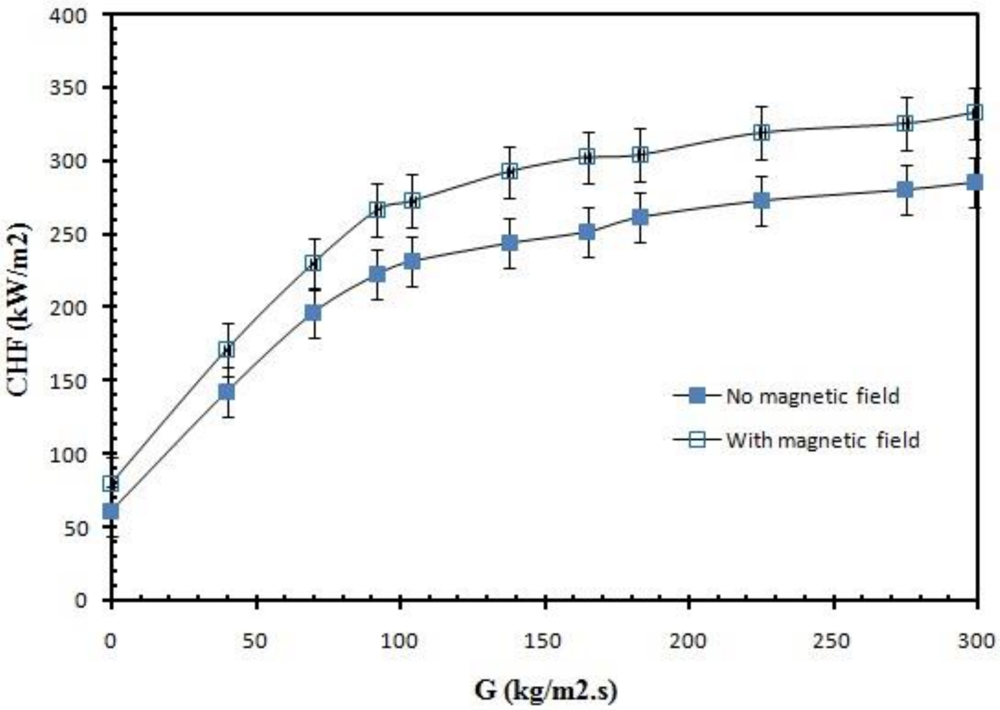

Figure 7 Effect of magnetic field on CHF of 0.01 vol.% ferrofluid.

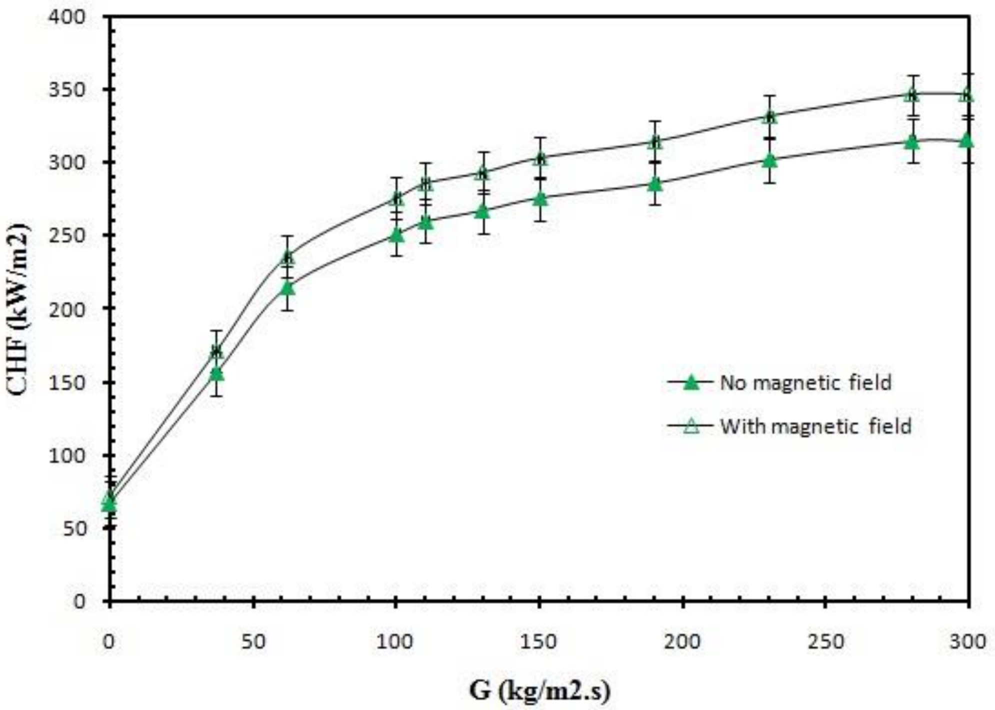

Figure 8 Effect of magnetic field on CHF of 0. 1 vol.% ferrofluid

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4 Conclusion

In this paper, an experimental setup is prepared to investigate the CHF behavior of the subcooled flow boiling of ferrofluids. The obtained results of this study showed that dispersing the nano-sized magnetic particles in pure water enhances the upper limit of heat flux in flow boiling so that the maximum increase of CHF was 19% and 32% for 0.01 and 0.1 vol.% of ferrofluids, respectively. In addition, the effect of applying external magnetic field on the CHF behavior of boiling ferrofluid flow has been studied. The results indicated that applying the magnetic field causes additional enhancement on CHF values especially in lower volume concentration of nanoparticles. The nanoparticles deposition on the tube inner surface and consequently improvement of surface characteristics such as nucleation site density, wettability and re-wetting properties could be mentioned as the main reason of this incident.

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چکیده

شار حرارتی بحرانی و مکان وقوع آن یکی از مسائل اساسی در طراحی مبادله‌کن‌های حرارتی نیروگاهی و راکتورهای هسته‌ای می باشد و جوشش مادون سرد هم در راکتورهای هسته ای و بویلرهای با ارتفاع کم از اهمیت ویژه ای برخوردار است. در کار حاضر تاثیر اعمال میدان مغناطیسی خارجی بر انتقال حرارت بحرانی برای جریان جوششی مادون سرد آب و سیال مغناطیس شونده در یک لوله قائم بصورت تجربی مورد مطالعه قرار گرفته است. با توجه به نتایج بدست آمده انتقال حرارت بحرانی در یک لوله قائم با تغییر سیال عامل به نانوسیال افزایش می‌یابد که عمدتا به دلیل رسوب نانوذرات بر روی سطح داخلی وتغییرمشخصات آن می باشد. همچنین اعمال میدان مغناطیسی باعث اصلاح مقدار انتقال حرارت بحرانی در نانوسیال مغناطیس شونده می‌شود. دلیل این موضوع جذب نانوذرات به سمت سطح به دلیل اعمال میدان مغناطیسی و افزایش ترشوندگی سطح می باشد.