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Research Paper

Experimental studies on ferrofluid pool boiling in the presence of external magnetic force

Mehmed Rafet Özdemir[a], Abdolali K. Sadaghiani[b], Ahmad Reza Motezakker[b], Sorour Semsari Parapari[b], Hyun Sun Park[c], Havva Yagci Acar[d], Ali Koşar[b,e,f,*]

[a] Mechanical Engineering Department, Marmara University, Istanbul, Turkey
[b] Faculty of Science and Engineering, Sabanci University, Istanbul, Turkey
[c] Division of Advanced Nuclear Engineering, Pohang University of Science and Technology (POSTECH), Gyeongsangbuk-do, Republic of Korea
[d] Koc University, Department of Chemistry, Istanbul, Turkey
[e] Center of Excellence for Functional Surfaces and Interfaces (EFSUN), Faculty of Engineering and Natural Sciences, Sabanci University, Tuzla, Istanbul 34956, Turkey
[f] Sabanci University Nanotechnology and Applications Center (SUNUM), Sabanci University, Tuzla, Istanbul 34956, Turkey

HIGHLIGHTS

- Boiling heat transfer characteristics of nanofluids was investigated with magnetic actuation.
- The effect of magnetic actuation of Fe_3O_4 nanoparticles was investigated at different mass fractions.
- Boiling heat transfer coefficient of the magnetically actuated system was significantly higher.
- Boiling heat transfer coefficient was not sensitive to the nanoparticle mass fraction.
- The results were supported with boiling images obtained from visualization studies.

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ABSTRACT

The past decade has witnessed rapid advances in thermal-fluid applications involving nanoparticles due to existing heat transfer enhancements. The main challenges in working with nanoparticles are clustering, sedimentation and instability encountered in many studies. In this study, magnetically actuated Fe_3O_4 nanoparticles were coated with a fatty acid and dispersed inside a base fluid (water) in order to avoid clustering, sedimentation and instability as well as to improve the thermal performance. Boiling heat transfer characteristics of the ferrofluids were experimentally investigated with magnetic actuation and compared to the results without magnetic actuation. Nanoparticle mass fraction was the major parameter. Boiling heat transfer coefficient of the magnetically actuated system was found to be significantly higher compared to the case without magnetic actuation. The results showed that boiling heat transfer coefficient was not sensitive to the nanoparticle mass fraction.

1. Introduction

Recent advances in nanotechnology have amplified the need for effective cooling in miniaturized systems [1–3]. For such applications, nanofluids were considered for providing superior heat transfer performance compared to pure liquids [4–7] so that they have been used in many areas including electronics, micro-reactors, air conditioning, fuel cells and near field radiative heat transfer processes due to their enhanced heat transfer characteristics [8–11]. Previous research has shown that nanofluids had a higher thermal conductivity compared to their base fluid [12–14]. Porous and rough surfaces have proven that the surface structure has a considerable effect on nucleate boiling [15,16]. The presence of nanoparticles in the base fluid also provided additional active nucleation sites thereby contributing to nucleate boiling heat transfer [17]. Moreover, a number of studies have reported that the random movement of nanoparticles (Brownian motion) and thermophoresis (Soret effect) augmented the energy transport of the entire system [11,18]. However, the performance of nanofluids is limited by some parameters such as clustering, sedimentation and precipitation, which deteriorate the stability of the nanofluids [19,20]. On the other hand, magnetically actuated nanofluids have wider application areas and could be utilized more effectively due to their higher

* Corresponding author at: Mechatronics Engineering Program, Sabanci University, Istanbul 34956, Turkey.
E-mail address: kosara@sabanciuniv.edu (A. Koşar).

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Nomenclature

A_{ht}	heat transfer area (m^2)
B	magnetic flux density (T)
C_{PL}	specific heat of the liquid (kJ/kg K)
C_{SF}	empirical constant for the influence of the liquid surface interaction (–)
F_{PF}	pressure correction factor (–)
F_{mag}	magnetic force (N)
h_{LG}	latent heat (kJ/kg)
h_{tp}	two-phase heat transfer coefficient (W/m^2 K)
$h_{tp,nb}$	two-phase heat transfer coefficient in nucleate boiling (W/m^2 K)
$h_{tp,0}$	two-phase heat transfer coefficient at the reference condition (W/m^2 K)
I	ampere (A)
nf	effect of reduced pressure on the exponent (–)
P	power input (W)
P_{crit}	critical pressure (Pa)
P_r	reduced pressure (Pa)
Pr	Prandtl number (–)
Q_{loss}	heat loss (W)
q	heating power (W)
q“	heat flux (W/m^2)
q_0“	heat flux at the reference condition (W/m^2)
R_P	surface roughness (m)
R_{P0}	surface roughness at the reference condition (m)
T_w	wall temperature (K)
T_s	surface temperature (K)
T_{sat}	saturation temperature (K)
V	voltage (V)
X_p	volume magnetic susceptibility of the magnetic particle ($m^3\,mol^{-1}$)
X_c	volume magnetic susceptibility of the carrier fluid ($m^3\,mol^{-1}$)

Greek

ΔT_{sat}	wall superheat (K)
μ_L	liquid viscosity (Pa s)
μ_o	permeability of free space ($N\,A^{-2}$)
σ	surface tension (N/m)
ρ_L	liquid density (kg/m^3)
ρ_G	vapor density (kg/m^3)

heat transportation capabilities. For example, Kurtoğlu et al. [21] showed that micro-pumps based on magnetically actuated nanoparticles do not contaminate the working fluid, which offers a significant advantage.

To date, rather few researchers have implemented magnetically actuated nanoparticles to increase the heat transfer performance and overall stability of the system [17,20–23]. For example, Şeşen et al. [17] investigated heat transfer characteristics of magnetically actuated nanofluids (Fe_3O_4) for single-phase flow and boiling conditions. They reported that the average heat transfer coefficient was enhanced by 29% with magnetic actuation in the single-phase experiments. On the other hand, two-phase average heat transfer coefficient was found to be 17% higher for the magnetic actuation case in boiling. Moreover, they observed that magnetically actuated nanoparticles delayed the formation of any clusters or deposition on the surface after the experiments.

Abdollahi et al. [24] investigated Fe_3O_4/DI water pool boiling and concluded that increasing the concentration of the nanofluid up to 0.1% raised boiling heat transfer coefficient while beyond this value a reverse trend was observed. Furthermore, their findings showed that the boiling heat transfer coefficient decreased in the presence of the positive magnetic field gradient and increased in the presence of the negative magnetic field gradient. The authors attributed this behavior to the fact that the magnetic force pulled the bubbles horizontally in elongated form. Therefore, the diameter of bubbles became larger, which made the bubble separation from the surface more difficult and consequently the heat transfer decreased due to the magnetic field. Sheikhbahai et al. [25] investigated the pool boiling performance of Fe_3O_4/ethylene glycol–water nanofluid under the external electrical field and showed enhanced boiling heat transfer coefficients and unaffected CHF (Critical Heat Flux). Their results indicated that applying an electric field reduced the surface tension of liquid–vapor interface, which lead to easier vapor bubble formation and increase in nucleate boiling heat transfer coefficients. Khoshmehr et al. [26] experimentally investigated boiling on a Silver cylinder with an aspect ratio of 10 and surface roughness of 689 nm using water and ferrofluids of two concentrations with and without magnetic fields. CHF was smaller for ferrofluids compared to pure water but was increased by 50% in the presence of the magnetic field.

Using numerical approach, Mohammadpourfard et al. [27] investigated nucleate pool boiling of ferrofluids on a horizontal plate under external magnetic field. In addition to higher heat transfer coefficients in ferrofluid nucleate pool boiling compared to water, their results indicated positive effect of magnetic field presence on nucleate pool boiling heat transfer. Using a Ni-Cr wire under the saturated pool boiling conditions, Lee et al. [28] experimentally investigated critical heat flux of a magnetite-water nanofluid. The increase in nanoparticle concentration provided an increase of about 170–240% in CHF compared to pure water. In their further study [29], they examined the effect of pressure on CHF of water-based nanofluids having Magnetite (Fe_3O_4) and Alumina (Al_2O_3) nanoparticles. CHF increased with pressure for both pure water and nanofluids. Mahmoudi and Abu-nada [30] numerically studied natural convective heat transfer of CuO-water nanofluids subjected to a magnetic field. They observed that strong magnetic fields would be effective and practical in increasing heat transfer performance of nanofluids. Shojaeian et al. [22] examined the magnetic actuation effect on the heat transfer performance and stability of the magnetic fluids during pool boiling. They found that the average two-phase heat transfer coefficient increased with magnetic actuation. In addition, they noticed that the sedimentation of nanoparticles on the surface was quite low in the magnetic actuation experiments compared to the experiments without magnetic actuation. The authors confirmed their findings by the surface analysis using SEM (Scanning Electron Microscopy) and EDS (Energy Dispersive Spectroscopy). In a recent study, Kandansamy et al. [23] investigated the influence of thermophoresis and Brownian motion of nanoparticles under magnetic fields. They concluded that the magnetic field exerts retarding force on the mixed convection flow and consequently enhances the Brownian motion of nanoparticles and heat transfer.

As emphasized in the abovementioned studies, magnetic actuation of nanoparticles inside a nanofluid significantly enhances heat transfer performance and stability of the system for both single-phase and boiling conditions. However, there are not many studies investigating this subject, particularly on visualization and assessment of major parameters. This study reveals the impact of magnetic actuation of Fe_3O_4 nanoparticles inside a water-Fe_3O_4 nanofluid in a range of mass fractions (0.033 − 0.13%) during boiling. Moreover, a visualization study was conducted in order to have a better understanding of underlying physical mechanism(s) in magnetically actuated nanoparticles system and to explain the results.