International Communications in Heat and Mass Transfer 75 (2016) 240–252

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Numerical investigation of non-uniform transverse magnetic field effects on the swirling flow boiling of magnetic nanofluid in annuli☆

M. Mohammadpourfard [a,*], H. Aminfar [b], M. Karimi [b]

[a] Department of Mechanical Engineering, Azarbaijan Shahid Madani University, Zip Code: 53751-71379, Tabriz, Iran
[b] Faculty of Mechanical Engineering, University of Tabriz, Tabriz, Iran

ARTICLE INFO

Available online 29 April 2016

Keywords:
Ferrofluid
Two fluid model
Swirling flow
Non-uniform transverse magnetic field
Annulus
Critical heat flux
Heat transfer

ABSTRACT

In this paper, swirling flow boiling of a dilute nanofluid (water and 0.1 vol%Fe_3O_4) in an annulus with a twisted fin on the outside of the inner wall in the presence of transverse magnetic gradient has been numerically investigated, using a two fluid model and a control volume technique. The results indicate that, in the boiling of swirling flow, the rate of the heat transfer increases. This phenomenon can be attributed to the effect of centrifugal force on the liquid phase flow and also reduction of the conductive sub-layer thickness that exists on the heated wall. The effects of improved surface wettability induced by nanoparticle deposition during the boiling process are accounted. The results demonstrate that the modified liquid property due to the existence of nanoparticles in the liquid has a negligible effect on the boiling heat transfer performance with dilute nanofluids while the improved surface wettability plays an important role and leads to reduction of the void fraction and consequently, an increase of critical heat flux. Applying a transverse magnetic field causes augmentation of the centrifugal force and results in increased flow turbulence. Furthermore, in the presence of the magnetic field due to magnetic force, the bubble departure diameter is reduced and bubble detachment occurs faster. Therefore, the critical heat flux will be increased. Swirling flow boiling in the presence of magnetic field is strongly suggested in devices requiring high heat transfer rates.

1. Introduction

Boiling heat transfer is a mode of heat transfer that occurs with a change in phase from liquid to vapor. Because of the very high heat transfer rate in boiling, it has been used to cool devices requiring high heat transfer rates. But this kind of the heat transfer has a limitation which is known as the critical heat flux. The critical heat flux condition is known by a sharp reduction of the local heat transfer coefficient and a sharp increase in surface temperature, which results from the replacement of liquid by vapor adjacent to the heat transfer surface.

Many different techniques have been considered for increasing the rate of heat transfer in forced convection and consequently increasing the critical heat flux. Swirling flow, using nanofluid as the working fluid and also applying an external magnetic field have been used in this study for investigating heat transfer enhancement.

Swirl flows are used in different modern technologies. The use of flow swirling is mainly aimed at heat transfer enhancement in power-engineering equipment, chemical technologies, and different industrial facilities [1]. In the literature, there are many studies that investigated the hydrothermal behavior of swirling flow and several correlations have been presented for evaluating the convective heat transfer coefficient and friction factor [2–4]. Gambill et al. [5,6] were the first to study the effect of flow swirling on heat transfer and its effect on the critical heat flux. They reported high CHFs, for water and ethylene glycol. Boscary et al. [7] experimentally investigated the CHF of water subcooled flow in swirl tube. Their experimental results are reasonably well predicted by a correlation proposed by Celata et al. [8]. Akhavan-Behabadi et al. [9] reported heat transfer enhancement and pressure drop characteristics during swirl flow boiling of R-134a. It should be noted that, in all of these investigations swirling flow is promoted by insertion of a twisted tape in the circular tube.

Nanofluids are colloidal suspensions engineered by dispersing nano-sized particles in traditional heat transfer fluids such as water and refrigerants. Already, there have been significant amount of studies on the effects of nanofluids on the boiling characteristics. Most of them investigated critical heat flux. Vafaei et al. [10] experimentally investigated the CHF of subcooled flow boiling of alumina nanofluid in a horizontal microchannel. The experiment showed an increase of 51%

☆ Communicated by W.J. Minkowycz

* Corresponding author. Tel./fax: +984134327566.
E-mail addresses: Mohammadpour@azaruniv.edu (M. Mohammadpourfard), hh_aminfar@tabrizu.ac.irand (H. Aminfar), Masoud.Karimi91@ms.tabrizu.ac.ir (M. Karimi).

http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.04.019
0735-1933/

Nomenclature

A_{lv}	interphase contact area $(1/m)$
A_Q	wall fraction influenced by nucleating bubbles
c_p	specific heat capacity (J/KgK)
d_b	bubble mean diameter (m)
d_{bW}	bubble departure diameter (m)
f	frequency (1/s)
$\vec{f}_D$	drag force (N)
$\vec{f}_L$	lift force (N)
$\vec{f}_W$	wall lubrication force (N)
$\vec{f}_{TD}$	turbulent dispersion force (N)
$\vec{f}_{VM}$	Virtual mass force (N)
H_{lv}	difference between specific enthalpies (J/Kg)
h_C	liquid single-phase heat transfer coefficient (W/m^2K)
$\vec{H}$	magnetic field vector (A/m)
H_x	magnetic field intensity component in x direction (A/m)
H_y	magnetic field intensity component in y direction (A/m)
I	Electric intensity(=75 A)
k_l	liquid thermal conductivity $(W/m\ K)$
k_B	Boltzmann constant $(=1.3806503\times10^{-23}$ J/K)
L	Langevin function
M	Magnetization (A/m)
m_p	particle magnetic moment (Am^2)
N_a	active nucleation site density$(1/m^2)$
q_T	total heat flux (W/m^2)
q_Q	quenching heat flux (W/m^2)
q_C	single-phase convection heat flux (W/m^2)
q_E	evaporation heat flux (W/m^2)
r_i	inner radius (m)
r_o	outer radius (m)
T	temperature (K)
u	velocity (m/s)

Greek symbols

α	void fraction
ρ	density (Kg/m^3)
μ_l	liquid dynamic viscosity $(Kg/m\ s)$
μ_0	magnetic permeability in vacuum $(=4\pi\times10^{-7}T\ m/A)$
μ_B	Bohr magneton$(=9.27\times10^{-24}Am^2)$
ξ	Langevin parameter

Subscripts

b	bubble
l	liquid
m	mean
v	vapor
p	particle

in critical heat flux under very low nanoparticle concentrations (0.1 vol%). It was found in their studies that nanoparticle deposition and a subsequent modification of the boiling surface are common features associated with nanofluids, which should be responsible for the different boiling behaviors of nanofluids. Kim et al. [11] conducted CHF experiments using water based alumina, zinc oxide and diamond nanofluids. The results indicated that CHF values of nanofluids were enhanced by up to 40–50%, always obtained at the highest mass flux.

The effects of external magnetic field on thermomagnetic convection of ferrofluids, which are special types of nanofluids, have been documented extensively by many researchers [12–16]. They presented that magnetizing force affects heat transfer rate and a strong magnetic field can control of magnetic convection of ferrofluids. For instance, Aminfar et al. [14–16] investigated the effects of different magnetic field on single-phase heat transfer characteristics of ferrofluids. Their results demonstrated the strong magnetic field effects on single-phase hydro-thermal behavior. Recently, the subject of boiling flow of ferrofluids under the effects of a magnetic field has been interested. Aminfar et al. [17] also conducted experimental studies on the effect of magnetic field on critical heat flux of ferrofluid flow boiling. The obtained results indicated that applying magnetic field caused an enhancement in CHF values of both pure water and ferrofluids. They attributed this phenomenon to changing water properties under the action of a magnetic field, single-phase convection heat transfer enhancement, suppression of nucleate boiling, and stabilization of boiling flow.

The above-mentioned sparse investigations of flow boiling of the ferrofluid under the influence of magnetic field are limited to boiling flow of the ferrofluid in a straight channel. These investigations don't include studies of the characteristic of swirling flow boiling and effects of centrifugal force in the presence of a magnetic field. The main aim of this paper is to investigate swirling flow boiling of a water based ferrofluid numerically under the effect of a non-uniform transverse magnetic field.

1.1. Problem description

In the first part of the present study, the influence of centrifugal force on flow boiling is investigated. For this purpose, flow boiling of the ferrofluid in a vertical annulus with three different heights of twisted fins on the outside of the inner wall has been considered and the results compared with the flow boiling in an annulus without fins and, finally, the height of the fin that from the aspect of the heat transfer performance, is more effective will be selected. These geometries are shown in Fig. 1 and their dimensions are summarized in Table 1. In the second part of this work, the effects of magnetic field on swirling flow boiling are investigated. As seen in Fig. 2, the applied magnetic field results from a wire of current, which is located parallel with the longitudinal axis and is also located in the center of the annulus. The working fluid is a dilute ferrofluid (water and 0.1 vol% Fe_3O_4) and the properties of the fluid studied and the particles are presented in Table 2. It should be noted that after selecting the desired geometry, deposition of nanoparticles have also been considered.

1.2. Governing equations

As already noted, the magnetic field is due to the electric current flowing through the wire, so the components of the magnetic field are given by [18]:

$$H_x(x,y)=\frac{I}{2\pi}\frac{x}{\sqrt{x^2+y^2}} \tag{1}$$

$$H_y(x,y)=-\frac{I}{2\pi}\frac{y}{\sqrt{x^2+y^2}} \tag{2}$$

and the magnitude of the magnetic field intensity, is as follow:

$$H(x,y,z)=H(x,y)=\frac{I}{2\pi}\frac{1}{\sqrt{x^2+y^2}}. \tag{3}$$

The effects of magnetic field on the viscosity and the thermal conductivity of the ferrofluid are considered negligible for this problem. Also, it is supposed that the flux of nanoparticles in the ferrofluid due to magnetophoresis and imposed temperature gradient [15] is negligible. In the present investigation for simulation of multiphase flow, the Eulerian–Eulerian model, which is known as the two-fluid model, has