Physica E xx (xxxx) xxxx–xxxx

Contents lists available at ScienceDirect

Physica E

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

Experimental investigation and simulation of flow boiling of nanofluids in different flow directions

Masoud Afrand[a,*], Ehsan Abedini[b], Hamid Teimouri[c]

[a] Department of Mechanical Engineering, Najafabad Branch, Islamic Azad University, Najafabad, Iran
[b] Mechanical Engineering Department, University of Hormozgan, Bandar Abbas, Iran
[c] Young Researchers and Elite club, Najafabad Branch, Islamic Azad University, Najafabad, Iran

ARTICLE INFO

Keywords:
Numerical simulation
Experimental investigation
Boiling of nanofluids
Horizontal tube
Vertical tube
Mixture model

ABSTRACT

In this work, the flow boiling of TiO_2/water and Al_2O_3/water nanofluids was investigated experimentally and simulated with two phases. Experimental results were obtained in two directions and compared together. The volume fraction and heat transfer coefficient obtained from the vertical tube were compared with those obtained from the horizontal tube. The results showed that the contours of vapor volume fraction in horizontal tube are completely different from the vertical tube, which is due to the buoyancy effect. Moreover, the effect of nanoparticles on both flow directions was almost the same, while heat transfer coefficient was not the same in these flow directions. Based on the experimental result, presence of nanoparticles in the base fluid cannot increase the heat transfer coefficient.

1. Introduction

Common liquids such as water, oil and ethylene glycol usually are used for heat transfer; while the efficiency of these liquids is low in the heat transfer processes. Thus, improving the liquid efficiency is considered by many researches. One of the main ways to improve the efficiency of liquids is the use of nanoparticles suspended in these fluids, called nanofluids. Many researchers have shown the thermal properties of nanofluids and their applications [1–6].

As is clear, boiling is the most effective heat transfer method because of its high performance due to latent heat transport, thus allowing the size, weight and volume of heat exchangers to be small. It can also improve thermal performance of components for industry and power plant processes. Therefore, boiling heat transfer plays a very vital role for an extensive number of applications in many industrial and technological areas, including energy production. As an example, subcooled boiling heat transfer can accommodate very high heat fluxes, and this can be appropriately engaged in the cooling of some components for fusion reactors. Furthermore, very compact heat exchangers can be manufactured thanks to the high heat transfer rate obtained with boiling heat transfer. Steam generators can be better designed if the boiling process is known in detail, thus improving the thermal cycle and the plant efficiency. Because of the importance of boiling, many researchers worked on simulations of subcooled boiling in vertical pipe [7–10] and horizontal pipe flows [11,12]. Lance and Bataille [7] studied the turbulence of the liquid in a bubbly flow. They used laser Doppler and hot-film anemometry for the experimental investigation. Their results show that turbulent kinetic energy increases strongly with void fraction. The liquid-phase turbulent structure of air–water, bubbly flow in a circular pipe has been investigated by Liu and Bankoff [8] experimentally. In this research, liquid-phase local velocities and turbulent stresses were measured simultaneously, using both one- and two-dimensional hot-film anemometer probes. They compared experimental data with some other data sources and existing models. Also, the important experimental results and parametric trends are summarized and discussed. In another research, they used a miniature dual-sensor resistivity probe to measure the radial profiles of void fraction, bubble velocity and bubble size [9]. Experimental results and parametric trends based on the effects of superficial velocities of both phases are summarized and discussed. Local measurement methods in bubble flows were discussed by Suzanne et al. [10] and local measurements using the different methods were presented as examples.

Kocamustafaogullari and Wang [11] investigated the internal phase distribution of co-current, air–water bubble flow in a transparent pipeline experimentally by using a double-sensor resistivity probe. The experimental results showed that the void fraction, interfacial area concentration and bubble frequency have local maxima near the upper pipe wall, and the profiles tend to flatten with rising void fraction. Kocamustafaogullari and Huang [12] performed an experimental study

* Corresponding author.
E-mail addresses: masoud.afrand@pmc.iaun.ac.ir, masoud_afrand@yahoo.com (M. Afrand).

http://dx.doi.org/10.1016/j.physe.2016.10.026
Received 18 May 2016; Received in revised form 10 June 2016; Accepted 22 October 2016
Available online xxxx

Nomenclature

d	diameter (m)
d_{BW}	bubble departure diameter (m)
E	energy (J/kg)
F	body force (N/m^3)
G	mass flow rate (kg/m^{2}s)
g	gravity acceleration (m/s^2)
h	convective heat transfer coefficient (W/m^2 K)
H	enthalpy (J/kg)
k	thermal conductivity (W/m K)
m	inter-phase mass transfer
$\dot{m}$	mass transfer due to evaporation and condensation(kg/s)
p	pressure (Pa)
q''	electric power (W/m^2)
S	source
T	temperature (°C or K)
t	time (s)
u	velocity (m/s)

Greek symbols

α	volume fraction of vapor or liquid
φ	contact angle (degree)
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

b	bulk
dr	drift
eff	effective
f	base fluid
in	inlet
k	summation index
l	liquid
t	turbulent
v	vapor
w	wall

on the internal structure of air–water flowing horizontally. The double-sensor resistivity probe technique was applied for measurements of local interracial parameters, including void fraction, interfacial area concentration, bubble size distributions, bubble passing frequency and bubble interface velocity. The experimental results provided good information about the local values of the void fraction, interracial area concentration and bubble passing frequency.

It can be noted that there are a number of papers on the prediction of boiling heat transfer of nanofluids [13–26] while comparisons between boiling of nanofluids in vertical and horizontal orientations remain unstudied. In the present study, the subcooled flow boiling of nanofluids is investigated. The volume fraction and heat transfer coefficient obtained from the vertical tube are compared with those obtained from the horizontal tube.

2. Mathematical modeling

For simulation of flow boiling, the mixture model is used. The equations being solved in the mixture model are as follows:

Continuity equation for the mixture is

$$\frac{\partial}{\partial t}(\rho_m) + \vec{\nabla}.(\rho_m \vec{u}_m) = \dot{m} \tag{1}$$

where $\dot{m}$ presents mass transfer due to evaporation and condensation. Also, $\vec{u}_m$ and ρ_m are the mass-averaged velocity and the mixture density, respectively, which are calculated by Eq. (2) and Eq. (3).

$$\vec{u}_m = \frac{\sum_{K=1}^{2} \alpha_k \rho_k \vec{u}_k}{\rho_m} \tag{2}$$

$$\rho_m = \sum_{K=1}^{2} \alpha_k \rho_k \tag{3}$$

The momentum equation for the mixture can be obtained by summing the individual momentum equations for all phases. It can be expressed as

$$\frac{\partial}{\partial t}(\rho_m \vec{u}_m) + \vec{\nabla}.(\rho_m \vec{u}_m \vec{u}_m) = -\vec{\nabla} p + \vec{\nabla}.[\mu_m(\vec{\nabla}\vec{u}_m + \vec{\nabla}\vec{u}_m^T)] + \rho_m \vec{g} + \vec{F} + \vec{\nabla}.\left(\sum_{K=1}^{2} \alpha_k \rho_k \vec{u}_{dr,k} \vec{u}_{dr,k}\right) \tag{4}$$

in which μ_m is the viscosity of the mixture and can be calculated from

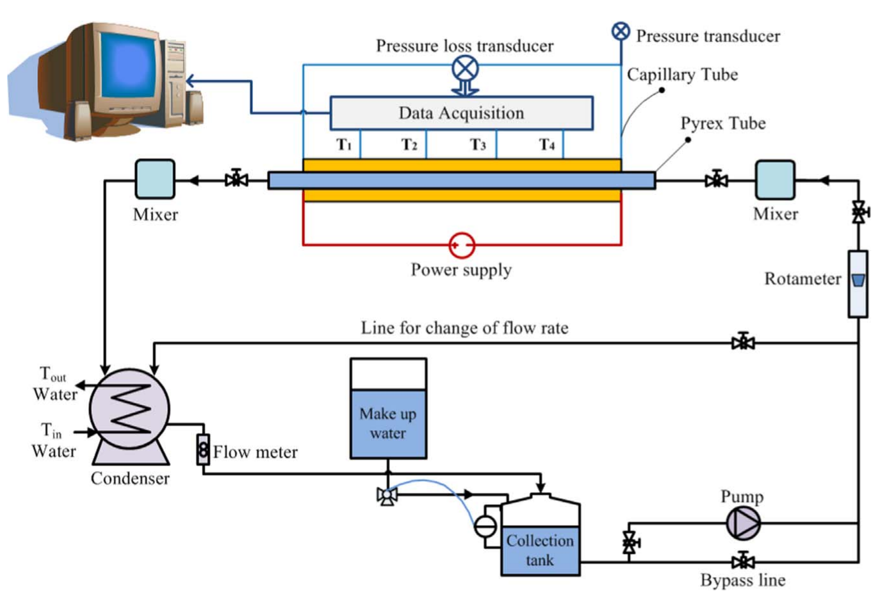

Fig. 1. Schematic diagram of the experimental setup.