International Journal of Heat and Mass Transfer 113 (2017) 59–69

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

# Experimental study on the nucleate boiling heat transfer characteristics of a water-based multi-walled carbon nanotubes nanofluid in a confined space

Guodong Xia [a,*], Mo Du [a], Lixin Cheng [a,b], Wei Wang [a]

[a] Key Laboratory of Enhanced Heat Transfer and Energy Conservation, Ministry of Education, College of Environmental and Energy Engineering, Beijing University of Technology, Beijing 100124, China

[b] Department of Engineering and Mathematics, Faculty of Arts, Computing, Engineering and Science, Sheffield Hallam University, City Campus, Howard Street, Sheffield S1 1WB, UK

ARTICLE INFO

*Article history:*
Received 9 January 2017
Received in revised form 3 May 2017
Accepted 6 May 2017

*Keywords:*
Nanofluids
MWCNTs
Nucleate boiling
Heat transfer
Enhancement
Mechanism

ABSTRACT

Experimental investigation of nucleate boiling heat transfer of a water-based multi-walled carbon nanotubes (MWCNTs) nanofluid in a confined space is presented in this study. First, the effects of four different surfactants on the stability of the nanofluids were investigated and the suitable surfactant gum acacia (GA) was selected for the boiling experiments. Then, the boiling experiments of the nanofluids with various volume fractions (0.005–0.2%) of the MWCNTs were conducted at a sub-atmospheric pressure of $1 \times 10^{-3}$ Pa and the test heat fluxes are from 100 to 740 kW/m$^2$. Furthermore, GA with four different mass fractions was respectively dissolved in the nanofluids to investigate the effect of the GA concentration on the boiling heat transfer. The effects of the heat flux, the concentrations of the MWCNTs and surfactants, the bubble behaviors and the surface conditions after the boiling processes have been analyzed. The results show that the MWCNTs nanofluid can enhance boiling heat transfer as compared to the base fluid. This is mainly caused by the nanoparticles deposition on the boiling surface result in increasing the surface roughness and reducing surface contact angle. It is also found that addition of GA can inhibit the deposition of the nanoparticles but may reduce the boiling heat transfer coefficient of the nanofluids. According to the experimental results, the maximum heat transfer coefficient enhancement ratio can reach 40.53%. It is also noticed that the heat transfer enhancement ratio decreases with increasing the heat flux at lower heat fluxes from 100 to 340 kW/m$^2$ while it increases with increasing the heat flux at higher fluxes from 340 to 740 kW/m$^2$. At the lower heat fluxes, the deposition layer increases the frequency of bubble formation and thus the boiling heat transfer is strengthened. While at the high heat fluxes, the increasing heat flux may strengthen the capability of the nanoparticles deposition and the disturbance of the nanoparticles and increase the enhancement ratio of heat transfer coefficient.



## 1. Introduction

As a new type of heat transfer medium, nanofluids have been attracting tremendous attention in the field of thermal science and engineering in recent years due to their high thermal conductivity, unique colloidal property and heat transfer behaviors [1–8]. Numerous researchers have conducted investigation into the heat transfer enhancement including single phase and phase change heat transfer using nanofluids [9–20]. In particular, the nucleate boiling heat transfer characteristics in confined spaces are of great interest to removing high heat flux in the microelectronic system, laser devices, green and highly efficient lighting with limited cooling spaces. Although a large number of researchers have investigated on the pool boiling heat transfer characteristics with plenty kinds of nanofluids in unconfined spaces, there lacks study of the characteristics of nucleate boiling heat transfer using the multi-walled carbon nanotubes (MWCNTs) nanofluid in confined spaces at sub-atmospheric pressures. Therefore, it is essential to conduct experimental investigation on the relevant topic.

Nanofluids which possess application prospects in the heat transfer field were firstly proposed by Choi [1] in 1995. From then on, numerous studies of heat transfer of nanofluids have been conducted to understand and explore their fundamentals and applications. The suspension stability and thermal conduction mechanism of nanofluids were studied by Xuan et al. [2], Assael [3] and many

* Corresponding author.
*E-mail address:* xgd@bjut.edu.cn (G. Xia).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.05.021

**Nomenclature**

| | |
|---|---|
| $h$ | heat transfer coefficient, W/m$^2$·K |
| $q$ | heat flux, W/m$^2$ |
| $T$ | temperature, K |
| $z$ | distance between two temperature measurement points, m |

*Greek symbols*

| | |
|---|---|
| $\lambda$ | thermal conductivity, W/m·K |
| $\eta$ | enhancement ratio of boiling heat transfer coefficient, % |

*Subscripts*

| | |
|---|---|
| f | working fluid |
| w | boiling surface |
| nf | nanofluids |
| dw | deionized water |

*Abbreviations*

| | |
|---|---|
| GA | gum acacia |
| MWCNTs | multi-walled carbon nanotubes |
| SEM | scanning electron microscopy |
| TEM | transmission electron microscopy |

other researchers [4,5]. Hwang et al. [6] prepared four kinds of nanofluids using MWCNTs, CuO and $SiO_2$ nanoparticles. They found that the thermal conductivity of nanofluids was higher than its base fluid and the thermal conductivity of MWCNTs nanofluid was the highest than other nanofluids under the same concentration.

As a new research frontier, nanofluids two phase flow and thermal physics is the subject of growing concern [7,8]. Investigation into the nanofluids phase change phenomena and complicated heat transfer mechanisms have intensively been performed over the past decade. Most researchers have found that the mechanisms of pool boiling heat transfer of nanofluids are different from those of conductive and convective heat transfer of nanofluids [11–13]. Yang and Maa [14] are possibly the first to conduct pool boiling experiments using nanofluids. Their experimental results have indicated that low concentrations of $Al_2O_3$ nanofluids with 50 nm diameter can enhance the nucleate pool boiling heat transfer. Xue et al. [15] studied the boiling curve, bubble pattern and contact angle of gum acacia (GA) solution and carbon nanotubes nanofluids. The results showed GA solution enhanced transition boiling heat transfer rate, since GA powder improved the wettability of water. In addition, the critical heat flux of nanofluids pronouncedly increases than that of GA solution due to the deposition of nanoparticles. Amiri et al. [16] performed some pool boiling experiments using carbon nanotubes nanofluid considering different functional groups of nanotubes. They investigated the pool boiling HTC of covalent nanofluids increases than that of deionized water, the heat transfer of non-covalent nanofluids became worse for the reason of the effect of heat resistance. Sarafraz et al. [17–19] study the pool boiling of the MWCNTs and $Al_2O_3$ nanofluids on several surfaces and conditions. About MWCNTs nanofluids, they found that the nucleate boiling of the nanofluids could still lead to the particle deposition, but the micro-finned surfaces broke the deposition to enhance the nucleation site and thus the boiling heat transfer increasing. Shoghl et al. [20] studied the pool boiling heat transfer of nanofluids with ZnO, $\alpha$-$Al_2O_3$ and MWCNTs. Their results indicate that the effects of boiling surface and properties of nanofluids to prove both of them may significantly influence the boiling heat transfer characteristics. For instance, the carbon nanotube-water nanofluids which improved the property of fluids and boiling surface characteristics could enhance the nucleate boiling heat transfer. Quite different results of nucleate boiling heat transfer with various surface conditions have been reported by researchers. Therefore, it is essential to explore and understand the various mechanisms governing the heat transfer processes.

According to the foregoing literature review, it is obvious that quite different results of boiling heat transfer with nanofluids and experimental conditions have been obtained. As pointed out by Cheng and Liu [7], there are still challenges to understand the boiling phenomena of nanofluids and their heat transfer mechanisms. Great effort should be made to achieve the complete and systematic knowledge in this aspect. In particular, it's still necessary to investigate and understand the heat transfer mechanisms through well designed and careful performed experiments and theoretical analysis.

Furthermore, the confined heat sink can be traced back to the ribbed radiator of CPU etc. In order to reduce the space and improve the heat efficiency of heat exchanger, flat plate heat pipe thermal spreader replaces the traditional radiator. The boiling in confined space condition just happens in this kind of heat pipe. Rops et al. [21] analyzed the nucleate boiling heat transfer on a spatially confined surface. They found that the depth of the boiling pot, the material of the bounding wall and the diameter of the inlet water supply didn't affect the enhancement of boiling heat transfer. Zhang et al. [22] reported an experimental investigation of phase-change phenomena in a small confined space. In the study, the boiling and condensation possessed dramatically impacted each other and the bubbles were limited not only by the distance between boiling and condensation surface, but also by the condensation process. Liu and Yang [23] observed that the boiling heat transfer characteristics were affected by lots of factor in confined space, especially vapor blowing, liquid suction and vapor waving resistance. They also found the enhancement ratio of heat transfer coefficient reduced by the condition of decreasing boiling space or increasing heat flux. However, the study of boiling heat transfer using nanofluids in confined spaces at sub-atmospheric pressures is very limited in the literature so far. Using nanofluid as working fluid seems a promising method of improving the heat transfer performance. The study on the mechanism of boiling heat transfer in confined with nanofluids is helpful to the application of nanofluids. Therefore, it is necessary to conduct the relevant study in this aspect.

The objectives of this paper are to experimentally investigate the complicated nucleate boiling mechanisms of nanofluids in a confined space under a sub-atmospheric pressure condition. First, the technology used for preparation of nanofluids is described. Then, experiments of nucleate boiling heat transfer of the MWCNTs nanofluids were conducted in a confined space at a pressure of $1 \times 10^{-3}$ Pa. The influences of heat flux, the concentration of nanofluids and surfactant on the heat transfer behaviors were presented. The scanning electron microscopy (SEM) photographs of boiling surfaces were used to analyze the modification by the deposition of nanoparticles. The roughness and contact angle of boiling surface and the visualization of the bubble behaviors were used to explain the boiling heat transfer mechanisms of the MWCNTs nanofluids.