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Investigation of flow boiling performance and the resulting surface deposition of graphene oxide nanofluid in microchannels

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ABSTRACT

Graphene oxide (GO)-water nanofluid was prepared and applied in flow boiling experiment in microchannels. Boiling heat transfer experiments were performed at various mass flow rates, with the nanofluid concentration ranging from 0 to 0.05 wt%. The heat transfer performance was found to be deteriorated for graphene oxide nanofluids. Nanofluid with higher concentration had lower heat transfer coefficient. Surface deposition was found after experiment for different concentration and flow rate. The nanoparticle interaction mechanism and absorption between nanoparticles was proposed to clarify the deposition process: higher temperature, concentration and fluid flow would accelerate the interaction and deposition process. The film-like shape of graphene oxide contributed to the formation of non-porous structure of deposition that blocked nucleation sites. An energy dispersive spectrometer (EDS) analysis of the deposit was carried out and the graphene oxide was found to be reduced chemically during boiling process and thus causing the deposition. Finally, the deposition morphology of graphene oxide was compared with those observed by other researchers and similar deposition characteristics were confirmed. It further indicates that the deposition which was reported to increase critical heat flux could have a negative effect on heat transfer coefficient.

1. Introduction

Improving energy utilizing efficiency is an effective strategy to solve current energy and environment problems. Microchannels have been investigated attractively due to its excellent heat transfer performance in both single phase and two phase problems, which has a lot of practical applications including aerospace electronics cooling, micro heat exchangers and micro reactors [1]. There have been a variety of methods to enhance boiling heat transfer in micro/mini channels [2], such as reentrant cavity [3], vapor venting [4] and microscale coatings [5]. These enhancing methods can be categorized into surface modification, changes of fluid property and flow pattern. In terms of change of fluid property, nanofluid, a base fluid containing nanoparticles, has drawn great attention since it was firstly proposed by Chol [6]. It has been used to enhance the heat transfer performance of fluids with low heat conduction by adding highly conductive nanoparticles. This method does not require any complex surface modification to obtain comparable heat transfer enhancement and thus it has been widely investigated in macroscale heat transfer experiments [7].

Nanofluid in microchannels has been used for heat transfer enhancement in single phase, mainly due to its improved heat conduction caused by the added nanoparticles with high conductivity [8–11]. Singh et al. [12] proposed that the heat transfer performance could also be affected by the particle movement apart from thermal conductivity. Few researches on flow boiling with nanofluid in microchannels have been investigated. Boudouh et al. [13] studied water-copper nanofluids convective boiling in narrow channels experimentally. Their results showed the nanofluid with increased concentration up to 50 mg/L can effectively increase local heat transfer coefficient, local heat flux and pressure and also reduce surface temperature. Vafaei and Wen [14] performed similar experiments and showed nanofluid could increase critical heat flux (CHF) in two ways: surface modification through deposition and bubble dynamics affected by suspended nanoparticles. Nevertheless, the heat transfer coefficient (HTC) of nanofluid was not studied. Wu and Zhao [7] simulated the bubbles in nanofluids and found they grew faster and the size was slightly higher than those in base fluid when using moving particle method developed by Koshizuka and Oka [15]. This indicates that the higher heat flux was drawn from the wall for the nanofluid. Xu et al. [16] studied Al_2O_3 nanofluids in a single silicon microchannel and found that nanofluids kept the bubbles from growing into elongated bubbles and avoided bubble coalescence, and thus reduced the transition

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Nomenclature

A	total heated area of fluid
A_{ch}	cross-sectional area of liquid flow
c_p	heat capacity of the fluid
G	mass flow rate
h	heat transfer coefficient
I	current
i_{lv}	latent heat
q''	heat flux
Q_{loss}	heat transfer to ambient
Q_{net}	heat absorbed by fluid
Q_{total}	total power input
T_w	average wall temperature
T_L	average liquid temperature
U	voltage
$u(P)$	uncertainty of parameter P
x	exit vapor quality

Subscript

in	inlet
out	outlet
w	wall
L	liquid

instability of flow pattern. This method finally increased the evaporation area for the thin liquid and heat transfer coefficient. Chehade et al. [17] used silver nanoparticles with low concentration in parallel minichannels. It was found the added nanoparticles increased local heat flux, local vapor quality and reduced wall temperature. The average increase of heat transfer coefficient reached 132% for 50 mg/L nanofluid.

The enhancement of nanofluid flow boiling heat transfer in microchannels was attributed to either bubble dynamic altering or higher thermal conductivity. Surface deposition condition of nanofluid was not mentioned. However, several researches noticed that nanofluid caused deposition and thus degraded heat transfer performance. Lee et al. [18] evaluated the effectiveness of Al_2O_3 nanofluid in microchannels, which found nanofluid could enhance single phase heat transfer effectively, especially in laminar region. For flow boiling heat transfer, it was observed that severe deposition formed clusters in the channels and even choked the flow. However, the reasons for such deposition were not given. Sarafraz and Hormozi [19] experimentally examined the subcooled flow boiling performance of CuO-water nanofluid inside a vertical tube. The deposition rate increased with the increasing concentration of nanofluid, and then heat transfer performance was worsened. It was also seen that fouling rate was a linear function of time. Ciloglu and Bolukbasi [20] proposed that surface particle deposition happened during the boiling process and could possibly block active nucleation sites. Such deposition was dependent on the interactions between nanoparticles and heated surfaces. If the surface deposition overwhelmed thermal conductivity enhancement of nanofluid, the HTCs could be deteriorated. And the primary reason for CHF enhancement is the deposition that caused surface characteristic enhancement (surface wettability, roughness and capillary wicking) [21–23].

So far, studies on the flow boiling of nanofluids are still limited and there is a discrepancy in previous results: the relationship between nanoparticle deposition and heat transfer coefficient has not been clarified. Those who reported heat transfer coefficient enhancement failed to mention surface deposition condition and surface deposition was reported to degrade heat transfer coefficient by other researchers.

Recently, graphene and graphene oxide nanofluid have been investigated extensively because of graphene's outstanding electrical and thermal properties [24–29]. The thermal conductivity of graphene nanofluid has been proved to have significant enhancement in water [30]. The two-dimensional geometry, high aspect ratio and stiffness of graphene and graphene oxide are the main reasons for the enhancement. Single phase heat transfer studies of graphene nanofluid were carried out by several researchers [31–33]. The enhanced heat transfer performance was attributed to the higher thermal conductivity of nanofluid. Park et al. [21] firstly performed an experiment of graphene nanofluid in pool boiling condition. The graphene oxide nanofluid showed 179% CHF enhancement, and graphene nanofluid showed 84% enhancement. Such enhancement was attributed to the self-assembly characteristic of the deposition layer since its morphology can change according to critical instability wavelength. Later, they used graphene oxide nanofluid in nuclear reactor in-vessel melt retention condition to investigate CHF enhancement during severe core-melt accidents [34,35]. In pool boiling test, the CHF enhancement for graphene oxide nanofluid was 40% at vertical position compared with distilled water. Lee et al. [36] investigated graphene oxide (GO)/water nanofluid flow boiling in a round tube which showed as much as 100% CHF enhancement. The heating surface was observed with scanning electron microscopy (SEM) and effect of the contact angle was studied after rigorous boiling. A significant deposition layer was observed and the surface wettability increased after the experiment, causing thin liquid more stable and thus delaying liquid film dry out.

Most of the studies of graphene nanofluid concentrated on pool boiling conditions CHF enhancement. Higher CHF can provide higher safety margin. If the enhanced safety margin is at the cost of lowered heat transfer coefficient or higher wall temperature, such enhancement of safety margin would be degraded. Few researches on nanofluid under flow boiling conditions have been performed and the results showed discrepancy. All of the researches about the deposition focused on the CHF enhancement or deteriorated heat transfer coefficient. Those who reported enhanced heat transfer coefficient of nanofluid in microchannels did not mention surface deposition conditions. The main objective of this investigation is to further study heat transfer performance of nanofluid under flow boiling condition in microscale. Graphene oxide nanofluid is chosen because of its advantages in heat transfer and graphene oxide nanofluid has never been investigated in microchannels. The relationship between heat transfer performance and surface deposition will be presented, followed by data analysis and comparison of deposition.

2. Experimental setup

2.1. Preparation of nanofluid

The preparation of nanofluid consisted of two steps. The graphene oxide was firstly manufactured by improved Hummers method [37,38]. Then a certain portion of GO was diluted with water into nanofluid with required concentration and after that was ultra-sonicated for one hour. The pH value of nanofluid was