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Study on flow boiling critical heat flux enhancement of graphene oxide/water nanofluid

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ABSTRACT

In this study, the flow boiling critical heat flux (CHF) using graphene oxide (GO)/water nanofluid was investigated under low pressure and low flow conditions. The 0.01 vol.% GO/water nanofluid is prepared for CHF enhancement test because recently, there are a lot of interests about graphene as an exceptional heat conduction material for thermal management and GO nanoparticles are more dispersed in water than graphene nanoparticles in terms of hydrophilicity. All experiments were carried out for round tubes with 1/2 in. diameter and 0.5 m heating length under low pressure and low flow (LPLF) at two fixed inlet temperatures (25 and 50 °C) and at four different mass fluxes (100, 150, 200 and 250 $kg/m^2 s$). It was found that the CHF of the GO/water nanofluid was more enhanced up to ~100% than the CHF of water as a base fluid. The causes of CHF enhancement were investigated through macroscopic observations, SEM observations and measurement of contact angles of the heated surfaces with depositions. Liquid film thickness affected by evaporation, entrainment and deposition mass transfer can be closely linked with wettability and GO properties.

1. Introduction

The CHF is characterized by a sudden reduction of the local heat transfer coefficient (HTC) that results from a transition from nucleate boiling to film boiling along with the heat transfer surface [1]. The CHF is generally more important in applications such as power generation for heat flux controlled systems, due to the burnout or failure of the integrity that occurs in heated surface. Therefore, it is very important to enhance the CHF in order to ensure the system safety and improve the system efficiency.

Many methods to enhance the CHF have been researched through the swirl flow using twisted tapes, the promotion of flow mixing, the altering of the characteristics on the heated surface and the changing of the surface tension. A new technique in recent years, among these methods, is nanofluid technology. Nanofluids are nanotechnology-based fluids engineered to enhance the thermal conductivity by dispersing and stably suspending nanoparticles in traditional heat transfer fluids [2]. One of the most interesting characteristics of nanofluids is their capability to significantly enhance CHF

The main objective of the present research is to do CHF experiments in flow boiling using GO/water nanofluid under LPLF conditions. Meanwhile, some flow boiling CHF experiments relevant to the present work were summarized as shown in Table 1.

Kim et al. [3] studied flow boiling CHF in nanofluids. They used a 0.01 vol.% alumina nanofluid characterized by nanoparticles with a size of ~50 nm. The results demonstrate that CHF enhancement up to ~30% can be achieved using the nanofluid. The authors found that the presence of the nanoparticles seems to have an effect on the burnout mode, making it more localized. Kim et al. [4] performed the CHF tests at 0.1 MPa and at three different mass fluxes (1500, 2000 and 2500 $kg/m^2 s$). The thermal conditions at CHF were subcooled. The authors showed that the maximum CHF enhancements were 53%, 53%, and 38% for alumina, zinc oxide, and diamond nanofluids, respectively. They concluded that an analysis of the boiling surface reveals that its morphology is altered by the deposition of the particles during boiling. Additionally, the wettability of the surface is substantially increased, which appears to correlate well with the observed CHF enhancement. Truong et al. [5] performed the CHF and heat transfer coefficients experiments with the test section deposited Al_2O_3 nanoparticles. The CHF values for the Al_2O_3 nanoparticles-coated tubing were found on average to be 28% higher than bare tubing at high mass flux of 2500 kg/m^2 s. However, no enhancement was found at lower mass flux of 1500 kg/m^2 s. They concluded that SEM images confirmed the presence of nanoparticle on the pre-coated surface, but, the coating is not uniform. So, the heat transfer coefficients

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Nomenclature

D	tube diameter (m)
G	mass flux (kg/m^2 s)
h	latent heat (MJ/kg)
I	measured current (A)
L	length of test section (m)
P	pressure (kPa)
q''	critical heat flux (MW/m^2)
T	temperature (°C)
V	measured voltage (V)
X	steam quality
z	tube length (m)

Greek symbol

φ	mass concentration of nanoparticles (%)

Subscripts

cr	critical
f	base fluids
fg	vaporization
in	inlet
ini	initial
m	mass
p	nanoparticles
sub	subcooling

Table 1
A summary of the CHF experiments from the literature.

Researchers	Working fluid	Inlet temperature (°C)	Mass flux (kg/m^2 s)	Test section (tube geometry)	Heated length (mm)	CHF enhancement
Kim et al. (2008) [3]	Al_2O_3/water (0.01 v%)	>80	1000	3/8 in SS316	240	30% (1500 kg/m^2 s)
			1500			
Kim et al. (2009) [4]	Al_2O_3/water	>80	1500	1/4 in SS316	100	53%(Al_2O_3/water, 2500 kg/m^2 s)
	ZnO/water		2000			53% (ZnO/water, 2500 kg/m^2 s)
	Diamond/water (0.001, 0.01, 0.1 v%)		2500			38% (Diamond/water, 2500 kg/m^2 s)
Truong et al. (2009) [5]	Deionized water	>80	1500	1/4 in SS316	100	28%
			2500	(Al_2O_3 deposited)		(2500 kg/m^2 s)
Kim et al. (2010) [6]	Al_2O_3/water (0.001, 0.01, 0.1 v%)	50	100	1/ in SS316	500	70.24% (50 °C, 100 kg/m^2 s)
		75	200			
			300			
Lee et al. (2010) [8]	TSP/water (0.2%, 0.4%, 0.6%)	50	100	1/2 in SS316	224	21.4% (TSP, 100 kg/m^2 s)
			200			
	Boric acid/water (0.2%, 0.4%, 0.6%, 0.8%)		300			12.4% (Boric acid, 100 kg/m^2 s)
			400			
			500			
Kim et al. (2011) [9]	Al_2O_3/water (0.0001, 0.001 v%)	75	500	3/8 in SS316 (pure and Al_2O_3 deposited)	400	78% (1500 kg/m^2 s)
			1000			
	Deionized water		1500			
Lee et al. (2012) [10]	Al_2O_3/water (0.01 v%)	25	100	1/2 in SS316	500	15% (Al_2O_3/water, 50 °C, 200 kg/m^2 s)
	SiC/water (0.01 v%)		150			41% (SiC/water, 25 °C, 150 kg/m^2 s)
		50	200			
			250			
Present Study	GO/water (0.01 v%)	25	100	1/2 in SS316	500	100% (25 °C, 250 kg/m^2 s)
			150			
		50	200			72% (50 °C, 250 kg/m^2 s)
			250			