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The characteristics and correlation of nanofluid flow boiling critical heat flux

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A R T I C L E I N F O

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As a preeminent working fluid, nanofluid has been attracted great attention since it was proposed based on nanotechnology. Flow boiling is familiar in heat transfer system and the critical heat flux is a key parameter for the design of thermal hydraulic. However, the research on the critical heat flux of nanofluid flow boiling is insufficient and no correlation is proposed for nanofluid flow boiling. Thus, the critical heat flux of nanofluid flow boiling is experimentally investigated in a vertical tube with the consideration of outlet pressure, mass flux, inlet subcooling, heating length and diameter, nanoparticle type and concentration. The results indicate that the critical heat flux of nanofluid flow boiling is enhanced (up to 18% in present work) compared with base fluid and the increasing radio is increased with increasing the mass flux, diameter and pressure, and with decreasing the heating length. In addition, the inlet subcooling, nanoparticle types (Al_2O_3, AlN) and concentrations (0.1 vol%, 0.5 vol%) have almost no significant influence. Moreover, the increasing is explained from the view point of adhering of liquid sublayer and deposition of nanoparticles. Furthermore, a correlation of nanofluid flow boiling critical heat flux is proposed by the experimental results with excellent accuracy and applicability.

1. Introduction

Since nanofluid was proposed in 1995 [1], the number of articles about nanofluid is increased progressively year after year. Nanofluid has already been a research focus because of its potential application in many high heat flux systems like nuclear power system. Recently, the thermal physical properties [2–10], convective and boiling heat transfer [11–22], and the application of nanofluid are studied widely [23–29]. As a key parameter for heat transfer system, critical heat flux (CHF) is worth deeply studying. It is well known that flow boiling is more familiar than pool boiling in heat transfer system, however, the research on the critical heat flux of nanofluid flow boiling is delayed compared with the research on the CHF of nanofluid pool boiling [30,31]. In 2008, Kim et al. [32] firstly studied the critical heat flux of 0.01 vol% Al_2O_3/H_2O nanofluid flow boiling by experimental method. The result indicates that the critical heat flux of nanofluid flow boiling is increased up to 30% under the condition of 0.1 MPa of outlet pressure, 8.7 mm of diameter, 240 mm of heating length and mass flux more than 1000 $kg{\cdot}m^{-2}{\cdot}s^{-1}$. After that, Kim et al. [33] experimentally studied the CHF of three kinds of nanofluid flow boiling under the condition of high mass flux (1500–2500 $kg{\cdot}m^{-2}{\cdot}s^{-1}$) at atmospheric pressure and the CHF are increased by 53%, 53% and 38% respectively for Al_2O_3/H_2O, ZnO/H_2O and Diamond/H_2O. These increasing is attributed to the modification of wettability. Vafaei et al. [34] studied the subcooled flow boiling of Al_2O_3/H_2O nanofluid in a microchannel with the diameter of 510 μm, the results indicate that the CHF is increased up to 51% with 0.1 vol% nanoparticle concentration due to nanoparticle deposition and the modification of heating surface. Ahn et al. [35] experimentally studied the CHF of nanofluid flow boiling on a short heating surface, the results show that the critical heat flux is increased. However, the outlet pressure wasn't mentioned. In 2010, Kim et al. [36] studied the CHF Al_2O_3/H_2O nanofluid flow boiling in a vertical tube, and the CHF is increased up to 70% for 0.01 vol% concentration, 50 °C inlet subcooling, 0.1 MPa of outlet pressure and mass flux of 100 $kg{\cdot}m^{-2}{\cdot}s^{-1}$. For further research, Kim et al. [37] experimentally investigated the critical heat flux of Al_2O_3/H_2O nanofluid flow boiling under high mass flux. In addition, the CHF of base fluid flow boiling with nanoparticle deposition was studied. Thus, the results indicate that the critical heat flux of Al_2O_3/H_2O nanofluid flow boiling is increased because of the deposition of nanoparticle on the

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Nomenclature

c_p	specific heat at constant pressure (kJ/kg·K)
d	diameter of nanoparticle (m)
D	diameter of section (m)
Fr	Froude number
g	acceleration of gravity (m/s^2)
G	mass flux (kg/m^2·s)
h_{fg}	latent heat (J/kg)
Δh	enthalpy (J)
I	electric current (A)
J	apparent velocity (m/s)
L	length of test section
n	sample number
p	pressure (Pa)
q	heat flux (W/m^2)
T	temperature (K)
u	velocity (m/s)
U	voltage (V)
x	quality

Greek symbols

ρ	density (kg/m^3)
μ	dynamic viscosity (kg/m·s)
σ	surface tension coefficient (N/m)
η	heating efficiency

Subscripts

b	bubble
CHF	critical heat flux
eq	equilibrium
g	gas phase
in	inner
l	liquid phase
nf	nanofluid
out	outlet
sub	subcooling

Abbreviations

ACD	adjusted coefficient of determination
CHF	critical heat flux
DW	deionized water
MAD	mean absolute relative deviation
MRD	mean relative deviation
RD	relative deviation
RSS	residual sum of squares
SEM	scanning electron microscope
TEM	transmission electron microscope

heating surface. As the specific area of graphene is greater than the conventional materials, Lee et al. [38] experimentally studied the CHF of water based graphene oxide nanofluid flow boiling at atmosphere. The result shows that the CHF of nanofluid is increased (up to 100%) and reason is that the contact angle of heating surface is decreased and the wettability is enhanced with the deposition of nanoparticles. Moreover, Lee et al. [39] studied the effects of magnetic field for magnetic nanofluid flow boiling critical heat flux. Increasing of CHF is found whether magnetic field exists or not and the enhancement is mainly due to the deposition of nanoparticle on the heating surface and it improves wettability. Aminfar et al. [40] also investigated the CHF of magnetic nanofluid flow boiling in a vertical annulus. The CHF of magnetic nanofluid flow boiling is increased under application of magnetic field and the reason for increasing is own to thermal physical properties, stability and delay on boiling incipience. Edel and Mukherjee [41] experimentally studied Al_2O_3/H_2O nanofluid flow boiling critical heat flux in a horizontal microchannel with 229 μm of diameter, 25.4 mm heating length and 0.1 MPa of pressure, their research shows the dry out decreased due to the enhancement of the thin film. Paul et al. [42] researched the rewetting of a vertical tube by Al/H_2O nanofluid and the result shows the rewetting in nanofluids takes place faster than base fluid and the deposition of nanoparticles alters the surface wettability and roughness causes the enhancement of the critical heat flux. So far, the researches on the critical heat flux of nanofluid flow boiling is extremely deficient. Pressure is a significant factor for flow boiling critical heat flux, however, no published researches focus on it as mentioned above. Furthermore, no correlation is proposed for nanofluid flow boiling and the application of nanofluid is restricted seriously. Thus, the critical heat flux of nanofluid flow boiling is experimentally studied with the consideration of outlet pressure and other factors, and a correlation with excellent accuracy and applicability is proposed for the critical heat flux of nanofluid flow boiling.

2. Experiment system

2.1. Experimental set up

To investigate the critical heat flux of nanofluid flow boiling, an experimental system is designed and carried out as shown in Fig. 1. This system includes a tank for nanofluid or deionized water, an ultrasonic vibration unit for preparing nanofluid and preventing nanoparticle from depositing, a gas loop for controlling pressure, a pump for forced circulation, a preheating section for controlling inlet subcooling of nanofluid and a vertical experimental section. With the consideration of heating length and diameter, several experimental sections are prepared with different heating length and diameter. Moreover, every experimental section will be replaced by a new one after each new kind of working fluid to avoid the influence of different characteristics of heating surface. Programmable DC power is used to heat experimental and preheating sections with 0.05% power uncertainty. The heating power

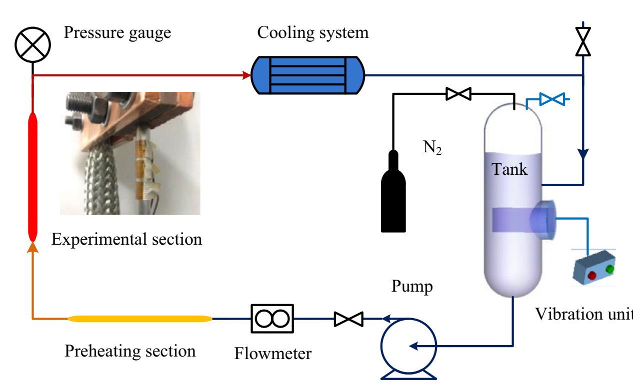

Fig. 1. Experimental system of nanofluid flow boiling CHF.