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Effects of thickness of boiling-induced nanoparticle deposition on the saturation of critical heat flux enhancement

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ABSTRACT

Pool boiling tests were conducted to determine the effects of nanoparticle coating thickness on critical heat flux in 0.01 vol.% alumina nanofluid under atmospheric pressure using Ni–Cr wire heaters. The thickness of nanoparticles coating layer was controlled by varying the boiling time for pre-coating in the nanofluid. The CHF enhancement curve was acquired with respect to time of pre-coating process. As the result, the CHF enhancement is remained or saturated regardless of boiling time over certain or critical pre-coating time while the CHF sharply increased in relatively shorter pre-coating time. The CHF is gradually decreased after the critical time region. The wetting characteristics and the Taylor wavelengths on the coating surfaces were investigated to explain the trend of CHF regarding the effects of coating thickness. The physical deposition characteristics such as the coating thickness and the porosity were studied to analyze the CHF trend. The porosity is a key parameter to determine the CHF saturated under conditions over a critical coating thickness.

1. Introduction

Boiling is an effective mode of heat transfer in comparison to single-phase heat transfer under the same flow conditions. It is favorable for systems that are operated with high heat flux and limited surface temperature. When the heat flux exceeds the designated value, a vapor film will form, covering the heater surface. This phenomenon is known as critical heat flux (CHF). CHF causes a rapid jump in temperature and serious damage to the heater system. Such accidents can lead to the leakage of radioactive material at nuclear power plants [1]. Therefore, it is important to predict and enhance the CHF value for improved safety and cost effectiveness. Improved CHF allows operation at thermal power levels higher than those possible in present power plants. The effect of improving CHF in several power plants was considered to be nearly as beneficial as building a new nuclear power plant but obviously without the construction costs.

Recently, nanofluids have attracted attention because of their unique influence on the CHF [2–5]. A nanofluid is a colloidal dispersion of nanoparticles in a base fluid. One of the most interesting characteristics of nanofluids is their capability to enhance CHF significantly at relatively dilute concentrations. Pool-boiling CHF tests were conducted in a variety of conditions depending on the material (metal, metal oxide, carbon allotrope, core–shell phase change material, etc.) and concentration (10^{-5} to 10 vol.%) used. CHF enhancement of up to 300% has been reported for nanofluids. This CHF enhancement is caused by the build-up of a nanoparticle deposition layer on the heater. This nanoparticle layer is formed through the vaporization of the microlayer underneath bubbles during the boiling of the nanofluid. Improved surface wettability has been considered to be the main reason behind enhanced CHF with nanofluids [6–8]. Another reason is the change in hydraulic instability due to the nanoparticles deposited on the surface [9–11]. The behavior of bubbles during boiling is influenced by the nanoparticles deposited on the surface. Deposition reduces the distance between the bubble departure sites, which is called the Taylor wavelength. The Taylor wavelength can be clearly observed in the film boiling region. The change of Taylor wavelength is very closely related to the nanoparticles deposited on the surface.

The deposited nanoparticles should be considered when boiling occurs over a long period of time. Unexpected results may occur when a surface is coated with a large thickness. These effects can be indirectly estimated in pool-boiling tests under a variety of nanofluid concentrations. In most of the experiments, the enhancement ratio of CHF was increased with increasing nanofluid concentration. The enhancement ratio becomes roughly constant when the concentration reaches a specific value. The thickness of deposited nanoparticles will continuously increase with boiling time. As a nanoparticle-deposited layer forms when the liquid film dries out,

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Nomenclature

A	heat transfer area [m^2]
D	diameter [m]
f	frequency [Hz]
g	acceleration due to gravity [m/s^2]
h	latent heat [J/kg]
H	heat transfer coefficient [W/m^2 K]
I	current [A]
K	thermal conductivity [W/m K]
L	heater length [m]
m	mass [kg]
n''	nucleation site density [m^{-2}]
Q	heat energy [W]
r	electric resistance [ohm]
R	thermal resistance [K/W]
q''	heat flux [W/m^2]
s	length [m]
U	overall heat transfer coefficient [W/m^2 K]
V	voltage [V]

Greek symbols

φ	fraction of mass [%]
ρ	density [kg/m^3]
σ	surface tension [N/m]
δ	thickness [m]
$\dot{\delta}$	growth rate of thickness [m/s]
ε	porosity
θ	receding contact angle [°]
β	heater orientation [°]
λ	wavelength [m]

Subscripts

b	bubble
$d1$	one dimension
f	fluid
g	gas
h	heater
M	mass
m	microlayer
p	particle
RT	Rayleigh–Taylor instability
S	system
w	wire
v	volume
Z	Zuber correlation for CHF

the relation between the nanoparticle deposition thickness and the boiling time should be proportional.

Several studies have focused on boiling time. One experimental study was conducted by varying the boiling time with nanofluids [12]. Kwark confirmed the effects of a nanoparticle-coated layer on the CHF and heat transfer coefficient. The wetting characteristics of the coated layer were confirmed by measuring the contact angle and observing the wicking velocity. The authors postulated that the enhanced CHF is caused by improved wetting capability. The CHF results were presented for a variety of nanofluid concentrations. The longest boiling time caused the largest enhancement of CHF for 1 g/l concentration. However, the case with the highest CHF did not match the case with the longest boiling time for 0.1 g/l and 0.015 g/l concentrations. Therefore, the relation between the boiling time and CHF enhancement is not clearly defined yet. The effect of the thickness of nanoparticle coating obtained by boiling in TiO_2 nanofluid was studied with respect to the CHF and boiling heat transfer coefficient [13]. The authors confirmed that there is a saturation point to CHF for nanofluids. Changing the high concentration is one of the ways to reach this point quickly under constant boiling conditions. The nanoparticle-coated layer detached from the heater surface at high concentrations after sufficient boiling. This phenomenon caused a decline in CHF compared with previous CHF data for an undamaged coating layer. The mechanism for the coating layer separating from the heater surface remains unknown. The nanoparticle-coated layer is generally porous. In other words, both vapor and liquid can be freely transported through this layer. When the coating layer is formed sufficiently thick and hard, this transport can be limited. The reason for the detaching of the layer could be explained by the impact of a sudden volume expansion due to the phase change and enhanced drag force resulting from the enlarged effective area. The nanofluid boiling system has a disadvantage like reduced CHF caused by detached coating layer.

The formation of the nanoparticle deposit layer proceeded simultaneously with the increase of heat flux. It is essential to understand the exact relation between the coating thickness and CHF without uncertainty. Fig. 1 and Eq. (1) refer to the just-introduced concept of layer effects on heat transfer. Eq. (1) is based on single phase heat transfer. Fig. 1 presents an interesting way to define the relation between the nanoparticle deposit thickness and heat transfer. The deposited nanoparticles function as the coating layer. In this region, heat would be transferred from the heater to the test fluid only by conduction. Thermal resistance increases when the layer is thick as described by Eq. (1). This concept also applies to the two phase heat transfer. In traditional boiling heat transfer, the condition of the heater surface is considered an important parameter. The coating layer that formed on the heater surface was porous when a nanofluid was used as the working fluid. Both the behaviors of liquid and vapor should be considered within the porous coating layer. The characteristics of the coating layer will influence the boiling heat transfer. Therefore, a disturbance to the heat transfer was temporarily referred to as thermal

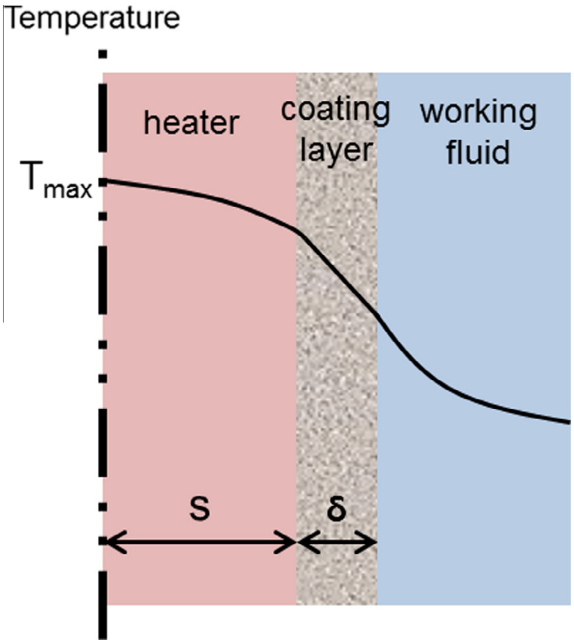

Fig. 1. Temperature distribution in general heater.