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NUCLEATE POOL BOILING HEAT TRANSFER ON A TITANIA NANOTUBE-COATED SURFACE

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ABSTRACT

Enhancing nucleate boiling using surface modification techniques has become to a major topic of interest in pool boiling studies. In this paper, experiments are conducted on a vertically oriented copper surface and a titanium surface coated with TiO_2 nanotubes. The nanotube coating is fabricated by a specific anodization process using ethylene glycol as the anodizing solution. A highly wetting dielectric coolant, Novec 7100, is used as the working fluid. A copper block heated by ceramic heater is used to simulate the high power density electronic. The nanotube coated surface shows a significant CHF (critical heat flux) enhancement up to 54% when compared to the plain copper. Various empirical correlations are applied to predict the experimental data. Among all the empirical correlations, the Rosehnow correlation and the Kutateladge correlation give good agreement with the measured data from the plain copper surface.

KEY WORDS: Electronics cooling, Heat transfer enhancement, Pool boiling, Dielectric liquid, Nanotube coating

1. INTRODUCTION

Thermal management has become to a critical concern in the microelectronics industry due to the increased power density of the electronic devices [1]. Among all the existing cooling methods, pool boiling with dielectric fluids is an efficient way to dissipate a large amount of heat. Coolants directly contact with the electronic devices and all the interfaces between the heated surfaces and the coolants are eliminated. The presence of liquid-vapor phase change can further enhance cooling capacity of the pool boiling systems. A lot of efforts have been made to improve pool boiling heat transfer by using different dielectric fluids and changing the environmental conditions (pressure, subcooling, etc.) and/or surface properties (surface roughness, porosity, wettability, etc.).

Novec 7100 is a dielectric fluid with prominent thermophysical properties, good environmental characteristics and large latent heat of vaporization. The boiling point of Novec 7100 is 61 °C, which is under the upper limits of most electronics. These characteristics makes it to be a suitable coolant for pool boiling. The pool boiling performance of Novec 7100 has been investigated on both plain surfaces and modified surfaces [2–4].

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Recently, improving heat transfer performance using nanomaterial coatings has become a focus in the pool boiling study. Chen et al. [5] observed an improvement of approximately 90% in CHF by coating TiO_2 nanotube arrays (TNTAs) interface on the pure Ti surface. The visualization study revealed that the initial bubbles are much smaller and depart at a higher frequency on the nanotube coated surface. They attributed the boiling improvement to more active nucleation sites, larger heating area and better wettability of the nanotube structure. Xu et al. [6] investigated the boiling performance on the nanotube coated surface with different anodization times and also observed increased CHF on the nanotube coated surface. However, their experiments were all conducted in water. In this work, the TiO_2 nanotube structure has been growing using a specific anodization process and the pool boiling heat transfer performance of a TiO_2 nanotube coated surface is investigated in Novec 7100. A polished cooper surface is used as the reference. Four empirical correlations are compared with the experimental data.

2. EXPERIMENTS

2.1 Experimental setup

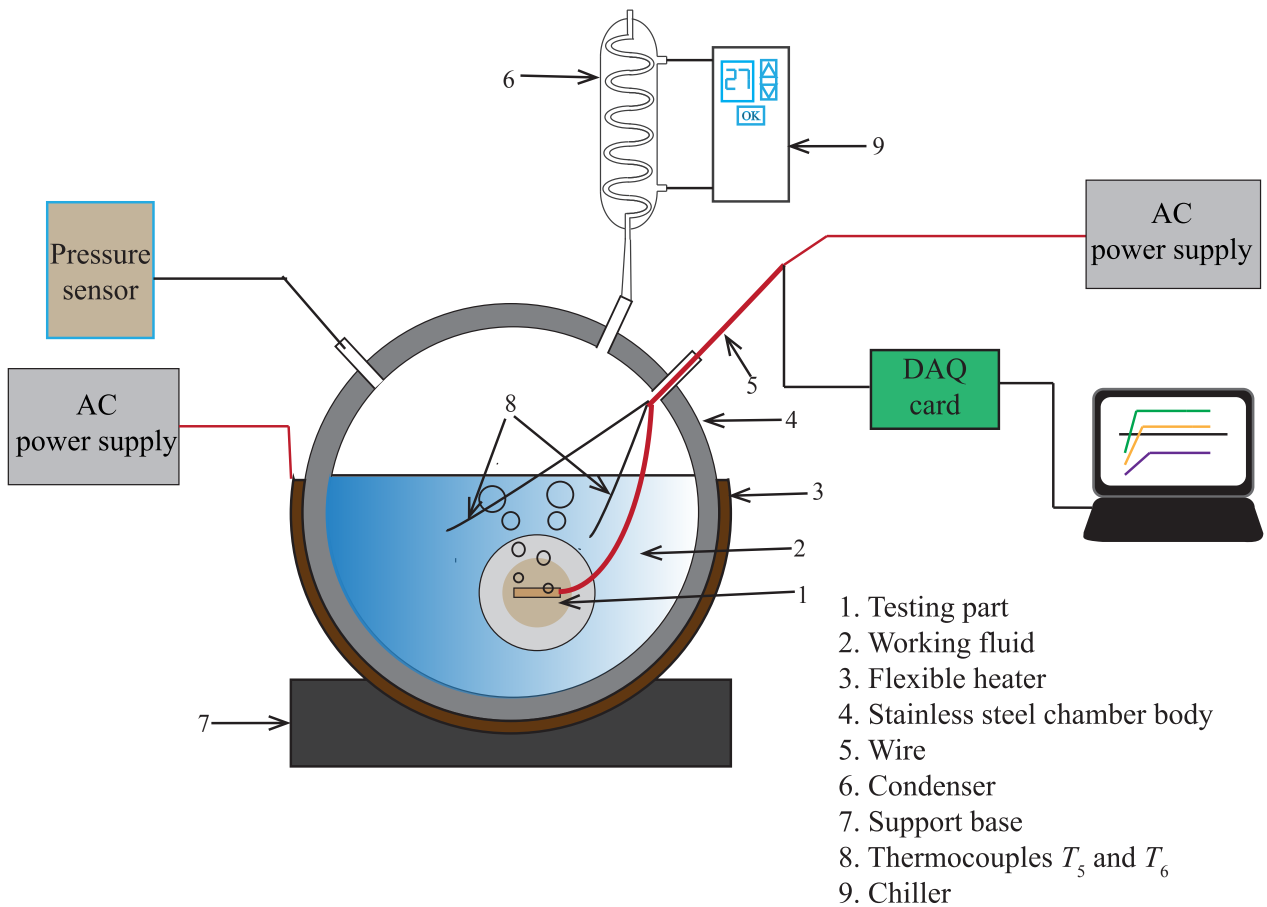

Fig. 1 Schematic of the experimental setup.

The schematic of experimental setup was shown in Fig. 1. The columnar boiling chamber was filled with Novec 7100 to a level about 30 mm above the heating surface. The chamber had a front and a back window made of Pyrex glass in order to perform visualization study. A flexible heater was attached to the chamber body, which is made of stainless steel, to heat up the Novec 7100 to its saturation temperature and maintain the saturation temperature during the experiments. Two thermocouples T_5 and T_6 were immersed into the Novec 7100 to measure the liquid temperature. All the heating wires and thermocouples were bound together and connected to the out-chamber equipment through one fitting. A reflux condenser was connected to the chamber to cool down vapors, prevent liquid loss as well as maintain the saturation condition. The pressure inside the chamber was monitored by a pressure transducer and was found always equal to the atmosphere pressure since the condenser was open to atmosphere at the top side.

2.1.1 Substrate preparation As shown in Fig.2, a 10 mm × 10 mm × 1 mm ceramic plate heater with a resistance of 10 Ω was adhered on the bottom side of the copper block. The block had a reversed T shape intersection surface and was 10 mm long perpendicular to the paper. Four thermocouples (T_1, T_2, T_3 and T_4) were embedded into the center of the block at positions of 24 mm, 15 mm, 5 mm and 1 mm far from the top

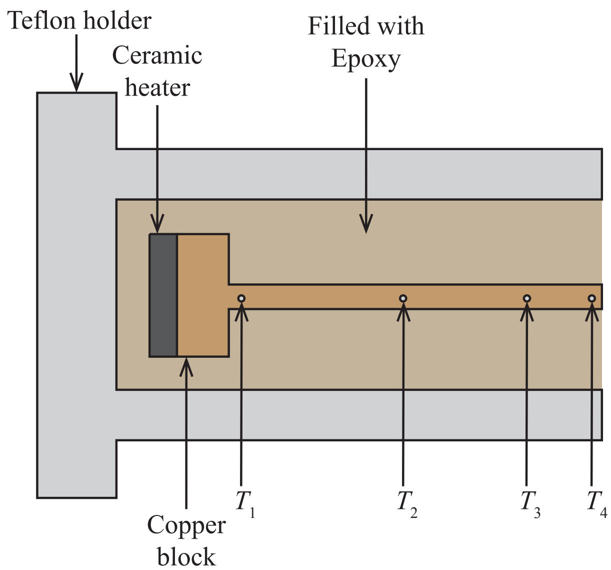

Fig. 2 Schematic of the test sample.

surface, respectively. The heater and the block were placed into a teflon holder filled with 3M epoxy to prevent heat loss. The epoxy level was kept flat with the top surface to ensure that heat only dissipates from the top surface of the block.

2.1.2 Preparation of TiO_2 nanotubes (TNTs) The nanotube structure was fabricated using a specific anodization precess. This anodization process had been described in details by Sun et al. [7, 8]. In their process, a platinum mesh performed as cathode and a titanium block was used as anode. Before the anodization, an ultrasonic clean machine was used to clean up the titanium block. Then a power of 60 V was supplied directly by a Keithley 2400 source-meter and the anodization process continued for 30 min to form the nanotube coatings on the block. Ethylene glycol, which consists of 0.3 wt% ammonium fluoride and 2 vol% deionized water, was used as the anodizing solution. All the anodization processes were conducted in room temperature. The test block with nanotube coating was finally rinsed with deionized water and dried in air after anodization.

2.2 Experimental procedures

A certain amount of Novec 7100 was first breathed into the chamber to a level about 30 mm above the heating surface. Then, the cooling loop should be opened before supplying power to the flexible heater. The working fluid was preheated by flexible heater for about 30 minutes to release the non-condensable gases. After this, the power to the flexible heater would heat up the Novec 7100 until it reaches its saturation temperature. The heater was then adjusted to an appropriate value to keep the system in saturation state. The power input to the test heaters was gradually increased and the temperatures were recorded when a steady state was established.

In our experiments, we considered the temperatures reach steady state if the temperature variation of T_4 in 1 minute is less than 0.2 K and an average value of 30 measured temperatures taken over 30 seconds after the steady state was calculated as the steady-state temperature in this level. The power input was then moved to next level and the data were recorded in identical procedure until a sudden increase of T_4 (2 K in 10 seconds in our experiments) occurred. The CHF value was regarded as the heat flux just before this sudden increase of T_4 and the power supply system should be shut down immediately to prevent the heating surface from burnout.

2.3 Data analysis

The heat flux through the surface can be calculated by the Fourier's law of heat conduction

$$\dot{q} = -k\frac{dT}{dz} \tag{1}$$

where k is the thermal conductivity of the copper and dT/dz is the temperature gradient along the copper block. Assuming one-dimension heat conduction, the Fourier's law of heat conduction becomes to:

$$\dot{q} = -k\frac{T_2 - T_4}{l_{24}} \tag{2}$$

or

$$\dot{q} = -k\frac{T_3 - T_4}{l_{34}} \tag{3}$$

where l_{24} is the distance between T_2 and T_4 and l_{34} is the distance between T_3 and T_4. Then the wall temperature T_w can be determined by the obtained heat flux $\dot{q}$ using equation

$$T_\mathrm{w} = T_4 - \frac{l_{4\mathrm{w}}\dot{q}}{k} \tag{4}$$

where $l_{4\mathrm{w}}$ is the distance between T_4 and top surface of copper block. The heat transfer coefficient h can be calculated as follows

$$h = \frac{\dot{q}}{\Delta T_\mathrm{sat}} \tag{5}$$

The term ΔT_sat is called wall superheat, which is given by:

$$\Delta T_\mathrm{sat} = T_\mathrm{w} - T_5 \tag{6}$$

and T_5 is treated as the saturation temperature of the Novec 7100.

The uncertainty of the thermocouple was estimated to be $\pm$ 0.056 °C based on the information provided by the manufacture. The uncertainty in the positions of the thermocouples was estimated to be $\pm$ 0.25 mm for the holes with diameter of 0.5 mm. Therefore, the uncertainty of the heat flux was estimated to be within 10% at heat flux below 10 $\mathrm{W/cm^2}$ and within 6% at heat flux above 10 $\mathrm{W/cm^2}$.

3. RESULTS AND DISCUSSION

Fig. 3 shows the boiling curves of the nanotube coated surface and the plain copper surface. The nanotube structure is grew on a thin titanium layer and is connected to the copper block using an Indium foil sheet. The best performance obtained on the nanotube coated surface is 52.2 $\mathrm{W/cm^2}$, which is 54% higher than that on the plain copper surface. However, the corresponding wall superheat at 52.2 $\mathrm{W/cm^2}$ is 135 °C, which beyonds the upper limits of most electronic devices. One possible reason for the high wall superheat could be the relatively poor thermal conductivity of titanium. Although the titanium layer is very thin, it could cause considerable temperature gap at high heat flux. Another possible reason may be the thermal contact resistance between the copper block and the nanotube structure. The discrepancy between run 1 and run 2 on nanotube coated surface could also be attributed to the uncertainty induced by the thermal contact resistance.

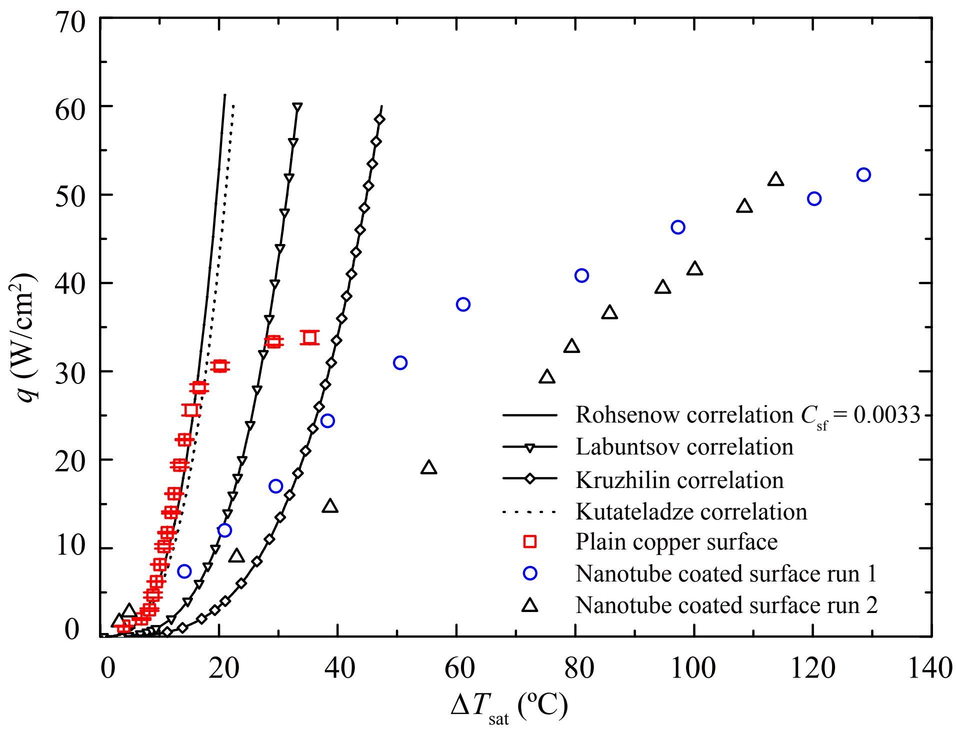

Fig. 3 Boiling curves in saturated Novec 7100.

Four empirical correlations are compared with the experimental data in Fig. 3. The thermophysical properties and the empirical correlations are summarized in Table 1 and Table 2. The saturation temperature during the experiments is 59 °C. Therefore, the reference temperature in Table 1 is 59 °C and the properties of Novec 7100 are calculated based on the data from Rausch et al. [13]. Since the value of the constant C_{sf} for the copper/Novec 7100 combination in the Rohsenow boiling correlation has not been systematically evaluated in the previous literatures, the constant C_{sf} is estimated at 0.0033 based on the experimental data as shown in Fig. 4. As a comparison, the constant C_{sf} for copper surface is 0.013, 0.212 and 0.215 in water, CCL_4 and Acetone, respectively [9, 14]. The small C_{sf} value indicates that this dielectric fluid has a relatively poor boiling heat transfer ability compared to the traditional used fluids. Both the Rosehnow correlation and the Kutateladge correlation are able to well predict the boiling curve of plain copper surface at both early and fully developed nucleate boiling region. The Kutateladge correlation even can fit the experimental results with no need for changing a constant. However, as the heat flux approaches CHF, the Rosehnow correlation and the Kutateladge correlation over predict the heat flux. In this region, the surface is fully covered by the bubbles. Since the heat transfer rate of the bubble film is very poor, the heat flux $\dot{q}$ increases at a reduced slope with the increasing wall superheat ΔT_{sat}. El-Genk and Bostanci [3] also reported that the heat flux increases slower in the high surface superheat region than that in the intermediate surface superheat region. Considering that the agreement is only invalid between 30.6 W/cm^2 and 33.8 W/cm^2, the Rosehnow correlation and the Kutateladge correlation are sufficiently good to predict the boiling performance of plain copper surface in Novec 7100. For the nanotube coated surface, all four correlations are in poor agreement with the measured data. More intensive investigations of the prediction methods for boiling curve on nanotube coated surface are required.

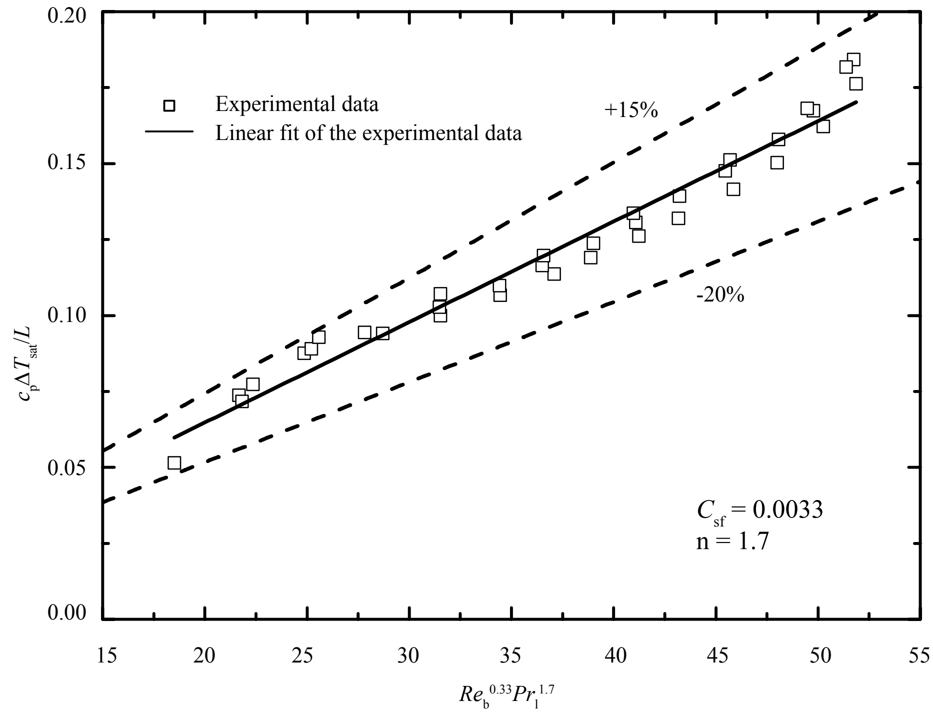

Fig. 4 Experimental data in terms of $\frac{c_p \Delta T_{sat}}{L}$ $vs.$ $Re_b^{0.33} Pr_l^{1.7}$.

4. CONCLUSIONS

Pool boiling experiments are conducted on both plain copper surface and nanotube coated surface using Novec 7100 as the working fluid. The nanotube structure is fabricated using a specific anodization precess. An improvement of maximum 54% in CHF is observed by using the TiO_2 nanotube coating. The Rosehnow correlation and the Kutateladge correlation are able to predict the boiling performance of plain copper surface in Novec 7100. For the nanotube coated surface, all the four empirical correlations are in poor agreement with the boiling curves, which indicates that the boiling mechanism of TiO_2 nanotube coated surface is very complicated and requires more intensive study in the future.

ACKNOWLEDGMENTS

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LIST OF SYMBOLS

C_{sf}	constant in Rohsenow correlation
g	gravity
L	latent heat
l	distance
l_*	pool boiling characteristic dimension, $[\frac{\sigma}{g(\rho_l - \rho_g)}]^{0.5}$
Nu_*	nucleate pool boiling Nusselt number, $\frac{hl_*}{k_l}$
Re_b	Reynolds number referred to the bubble diameter, $\frac{\dot{q}}{\mu L}\sqrt{\frac{\sigma}{g(\rho_l - \rho_g)}}$

Table 1 Physical properties of Novec 7100.

	Unit	Novec 7100
Reference pressure	kPa	101
Saturation temperature	K	332.15
Surface tension	N/m	10.12×10^{-3}
Latent heat	kJ/kg	111.96
Liquid density	$\mathrm{kg/m^3}$	1424.34
Vapor density	$\mathrm{kg/m^3}$	9.142
Thermal conductivity	$\mathrm{W/m \cdot K}$	0.069
Dynamic viscosity	$\mathrm{Pa \cdot s}$	4.37×10^{-4}
Specific heat	$\mathrm{kJ/kg \cdot K}$	1.183
Kinematic viscosity	$\mathrm{m^2/s}$	0.307×10^{-6}

Table 2 Nucleate pool boiling heat transfer correlations.

Author	Correlation
Rohsenow[9]	$\frac{c_\mathrm{p}\Delta T_\mathrm{sat}}{L} = C_\mathrm{sf}[\frac{\dot{q}}{\mu L}\sqrt{\frac{\sigma}{g(\rho_\mathrm{l}-\rho_\mathrm{g})}}]^{0.33}(\frac{c_\mathrm{p}\mu}{k_\mathrm{l}})^n$ or $\frac{c_\mathrm{p}\Delta T_\mathrm{sat}}{L} = C_\mathrm{sf} Re_\mathrm{b}^{0.33} Pr_\mathrm{l}^n$.
Kutateladze[10]	$h = [3.37 \times 10^{-9}\frac{k_\mathrm{l}}{l_*}(\frac{L}{c_\mathrm{p}\dot{q}})^{-2}M_*^{-4}]^{\frac{1}{3}}$ where $l_* = [\frac{\sigma}{g(\rho_\mathrm{l}-\rho_\mathrm{g})}]^{0.5}$ is the pool boiling characteristic dimension and $M_*^4 = \frac{\frac{\sigma g}{\rho_\mathrm{l}-\rho_\mathrm{g}}}{(\frac{p}{\rho_\mathrm{g}})^2}$.
Labuntsov[11]	$h = 0.075[1 + 10(\frac{\rho_\mathrm{g}}{\rho_\mathrm{l}-\rho_\mathrm{g}})^{0.67}](\frac{k_\mathrm{l}^2}{\nu\sigma(T_\mathrm{sat}+273.15)})^{0.33}\dot{q}^{0.67}$
Kruzhilin[12]	$Nu_* = 0.082(\frac{L\dot{q}}{g(T_\mathrm{sat}+273.15)k_l}\frac{\rho_\mathrm{g}}{\rho_\mathrm{l}-\rho_\mathrm{g}})^{0.7}[\frac{(T_\mathrm{sat}+273.15)c_\mathrm{p}\sigma\rho_\mathrm{l}}{L^2\rho_\mathrm{g}^2 l_*}]^{0.33}Pr_\mathrm{l}^{-0.45}$ where $Nu_* = \frac{hl_*}{k_\mathrm{l}}$ is the nucleate pool boiling Nusselt number.

T	temperature
ΔT	wall superheat
Subscripts	
sat	saturation

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