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Analysis on hysteresis in nucleate pool boiling heat transfer

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Abstract—Many experiments reported for nucleate pool boiling heat transfer from microelectronic assemblies or porous surfaces in dielectric fluids have shown the existence of hysteresis phenomenon, which is known as a temperature overshoot (TOS) in boiling incipience and constrains engineering applications. Here, theoretical analysis has been carried out. It confirms that hysteresis may occur during both the boiling incipience and the boiling development. Hence, a new type of hysteresis, termed Temperature Deviation (TD), is described. Using thermodynamic nucleation, the physical mechanisms for both TOS and TD are analyzed in detail. Three parameters for quantitatively understanding the hysteresis phenomenon and possible measures for remedying it are proposed and discussed.

1. INTRODUCTION

RECOGNITION of the boiling hysteresis phenomenon dates back to the beginning of the 1950s, when Corty and Foust [1] reported formally that the immediate past history of the boiling surface in liquid ether, normal pentane or refrigerant R-113 had a pronounced effect on the superheat required for incipience, which was far in excess of that required in normal boiling conditions. This phenomenon was termed as hysteresis of temperature overshoot (TOS), i.e. the wall surface temperature becomes highly superheated preceding the initiation of boiling bubbles for transition from natural convection in liquid pool to nucleate boiling.

Since the late 1960s, Bergles *et al.* [2], Reeber and Frester [3], Oktay [4] and Bar-Cohen and Simon [5] presented extensive researches on boiling hysteresis in the field of immersion cooling systems for thermal control of microelectronic components. It makes clear that, the boiling hysteresis may affect the safe operation of high-power density components, and hence, impeded engineering applications of pool boiling cooling technology.

The effective utilization of industrial waste heat and the exploitation of renewable energy sources require new heat transfer enhancing technologies, and so, challenged the world since the late 1970s. Commercial porous surfaces have proven to be an effective means for enhancing boiling heat transfer, but numerous experiments make sure the hysteresis phenomenon was more prominent than that on smooth surfaces [6, 7]. The temperature overshoot or the delayed natural convection phenomena were easily recognized, and the discrepancies between the boiling curves obtained with increasing and then decreasing heat flux, as shown in Fig. 1, were known as the definition of boiling hysteresis.

It is of great significance to understand thoroughly the hysteresis phenomena so as to advance the above-mentioned researches on boiling heat transfer. This paper focuses on the analysis of the boiling hysteresis. The hysteresis characteristics of nucleate pool boiling heat transfer have been generalized and the physical mechanism is further discussed.

2. BOILING HYSTERESIS CHARACTERISTICS

Recent experiments [8–11] reported for pool boiling heat transfer on smooth or porous surfaces, along tubes or plates, have shown that the boiling hysteresis curves were not always similar to that of Fig. 1, and may exist after boiling initiates, as shown in Fig. 2.

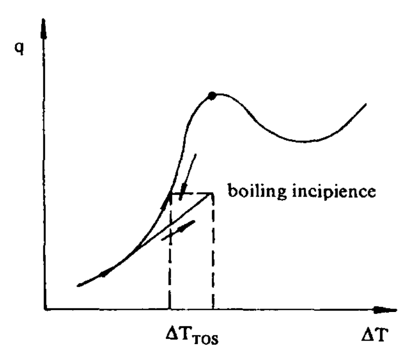

FIG. 1. Temperature overshoot in boiling incipience.

NOMENCLATURE

A	hysteresis area [W m^{-2} K]
F	free energy [kJ]
g	Gibbs function per unit mass [kJ kg^{-1}]
h_{fg}	latent heat of vaporization [kJ kg^{-1}]
H	Planck constant
K	Boltzmann constant
L	length [m]
M	mass [kg]
n	constant, molecular number per unit liquid volume
P	pressure [Pa]
q	heat flux [W m^{-2}]
r	radius of a vapor bubble [m]
R	universal gas constant
T	temperature [K]
ΔT	wall superheat [K].

Greek symbols

α	half bubble angle, Fig. 5
β	contact angle
θ	half conic angle
ρ	density [kg m^{-3}]
σ	surface tension [N m^{-1}]
Φ	conic angle.

Subscripts

l	liquid
v	vapor
s	saturation
g	residual gas
i	incipient boiling condition.

The disagreement of boiling curves differs from the boiling incipient hysteresis (TOS). We concluded that, boiling hysteresis may exist in the boiling developing process, which we termed as another type of hysteresis—Temperature Deviation (TD) hysteresis [8, 9].

As reported in ref. [4], hysteresis-type behaviour during the onset of nucleate boiling was irregular. The traditional description of TOS hysteresis does not completely reflect the hysteresis characteristics of nucleate pool boiling. We subdivided the boiling hysteresis phenomenon into two kinds: (I) TOS hysteresis and (II) TD hysteresis, generalized in Fig. 2 [9]. TOS hysteresis occurs at boiling incipience, while TD hysteresis may occur in the transitional region between partial and fully-developed nucleate pool boiling. Boiling heat transfer on smooth surfaces may exhibit TD hysteresis phenomenon, not TOS, as has been made shown in ref. [9]. TOS hysteresis, prominent for rough or porous surfaces, has received significant attention because of its serious effects on safe operation of microelectronic equipment. TD hysteresis has not been clearly understood, and may possibly be the main reason for uncertainties of boiling heat transfer data and irregularities in boiling curves, which impede the advance in theoretical researches on nucleate pool boiling.

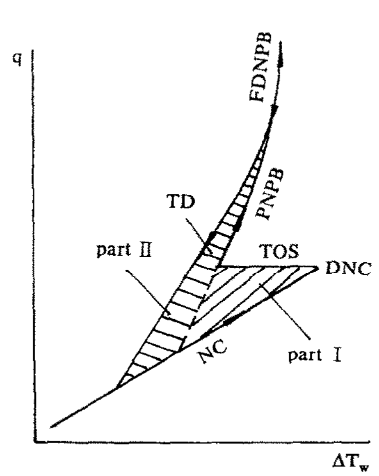

Fig. 2. Characteristic curves of nucleate pool boiling hysteresis: FDNPB—fully-developed nucleate pool boiling; PNPB—partial nucleate pool boiling; DNC—departure from natural convection; NC—natural convection.

3. BOILING HYSTERESIS MECHANISMS

The nucleation of vapor bubbles from embryonic vapor/gas pockets in microcavities on the heated surface has been proven to account for boiling incipience and much of the ebullient heat transfer from metallic surfaces to water and other conventional fluids [12]. For a machined metallic surface, there exist a wide range of cavity sizes. If this surface is immersed in the liquid with good wetting characteristics, a large percentage of the cavities would be filled by the liquid. Only a small percentage of cavities would trap some residual gas in them. These cavities might become the first nucleation sites.

Consider an embryonic bubble of radius r_c growing out from a conical cavity on a heated wall as shown in Fig. 3. The bubble may include some noncondensable gas. The mechanical stability of the bubble requires that the internal pressure exceed the external or local ambient pressure by an amount proportional to the surface tension divided by the radius of curvature at the interface. Assuming the bubble to be hemispherical and recognizing the presence of the initial residual gas, the mechanical equilibrium for this embryo bubble is:

$$P_v + P_g - P_l = \frac{2\sigma}{r_c} \quad (1)$$

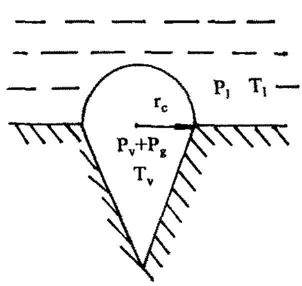

FIG. 3. Activation of the first bubbles.

where P_v and P_g are the vapor partial pressure and initial partial pressure of the residual gas in the bubble respectively.

According to the thermodynamic nucleation theory, the liquid superheat needed for this embryonic bubble to grow should be

$$\Delta T_{w_1} = T_{w_1} - T_s = \frac{T_s}{\rho_v h_{fg}}\left(\frac{2\sigma}{cr_c} - P_g\right) \quad (2)$$

where c is a constant depending on the thermal layer thickness surrounding the bubble. Assuming the residual gas is a perfect gas, we have

$$P_g = \frac{3M_g RT_v}{4\pi r_c^3} \quad (3)$$

where M_g is the initial mass of residual gas in the cavity. Equation (2) can then be expressed as

$$\Delta T_{w_1} = \frac{T_s}{\rho_v h_{fg}}\left(\frac{2\sigma}{cr_c} - \frac{3M_g RT_v}{4\pi r_c^3}\right). \quad (4)$$

3.1. *TOS hysteresis*

TOS hysteresis is a phenomenon occurring at boiling incipience for some liquid–surface combination. The first bubble generation emerges only at individual spots on the surface. These spots correspond to the cavities in which only a small amount of residual gas preexisted. Thus, the liquid superheat needed for this first bubble generation is large and can be predicted by equation (4).

After the departure of the first bubbles, more residual gas (vapor) will be trapped in these cavities, which causes the wall superheat to decrease in the next bubble generation. This is the so-called 'vapor gathering'.

The liquid superheat needed for further bubbles to grow will be

$$\Delta T_{w_2} = \frac{T_s}{\rho_v h_{fg}}\left(\frac{2\sigma}{cr_c} - \frac{3M_{g_c} RT_v}{4\pi r_c^3}\right) \quad (5)$$

where M_{g_c} is an equivalent mass of the new residual gas–vapor mixture in the cavities, and ΔT_{w_2} is the normal boiling superheat at the given heat flux. Since $M_{g_c} > M_g$, then $\Delta T_{w_2} < \Delta T_{w_1}$ at the same wall heat flux. So, TOS hysteresis will occur at boiling incipience. The temperature overshoot can be thus defined as:

$$\Delta T_{TOS} = \Delta T_{w_1} - \Delta T_{w_2} = \frac{3T_s T_v R}{4\pi r_c^3 \rho_v h_{fg}}(M_{g_c} - M_g). \quad (6)$$

Hence, the more residual gas (vapor) trapped in the cavity, the less the temperature overshoot that would exist at boiling incipience, and TOS hysteresis would be eliminated, if the residual mass M_g is equal to the equivalent mass M_{g_c}.

The porous surfaces, on which there exist large numbers of cavities being easily drowned fully or partly by the liquid and reactivated in the normal boiling process, usually have a larger temperature overshoot than the plain surfaces. But for those porous surfaces with large numbers of active cavities (such as reentrant cavities), the temperature overshoot occurs less frequently [13].

The objectives for developing an enhanced boiling surface, of course, should be to reduce both the temperature overshoot prior to incipient boiling of the liquid coolant and the wall superheat in the established boiling process.

3.2. *TD hysteresis*

TD hysteresis may occur in the boiling development process, and can be interpreted by further refining the vapor propagation model [9]. The increase in number of activated cavities on the surface depends both on the increase of the wall surface superheat and on the activation of neighboring cavities.

During the growing of the first bubbles, neighboring cavities which retained less residual gas or no residual gas might be activated at lower wall superheats by vapor propagation or vapor covering as shown in Fig. 4. During the growth of the first bubble, the bubble interface spreads along the surface. The vapor front would penetrate into the neighboring cavity if the liquid contact angle β satisfies the condition

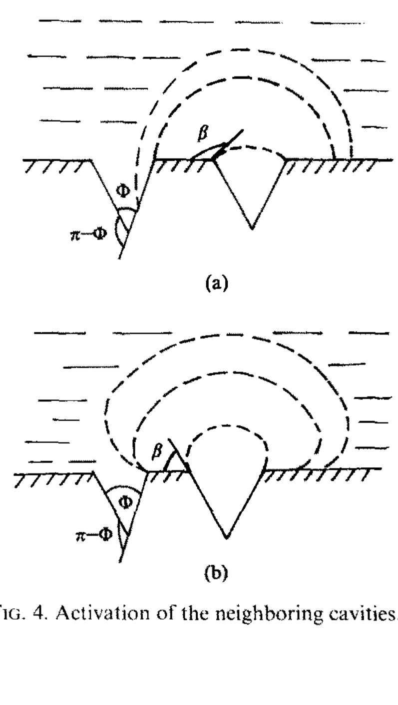

FIG. 4. Activation of the neighboring cavities.

$\beta > (\pi - \Phi)$. Thus the neighboring cavity would be completely filled with gas (vapor) and hence, be activated by this vapor propagation (Fig. 4(a)). If $\beta < (\pi - \Phi)$, that is, a neighboring cavity having a small conical angle, Φ, or a liquid having a small contact angle, β (Fig. 4(b)), the cavity might initially have a small amount of gas in it and not be activated at the initial wall superheat. If the first growing bubble front covers this cavity, the liquid in the cavity would be separated from the main liquid pool and locally highly superheated by the heated wall. The small embryonic bubble would grow by liquid evaporation and might be activated in the next bubble generation (Fig. 4(b)).

The new nucleation centers will not only enhance boiling heat transfer, but also activate other neighboring cavities, i.e. the further vapor propagation, until fully-developed nucleate pool boiling is reached. If the heat flux is then decreased, those cavities which were not activated in increasing heat flux, are now in their active state. According to equation (3), they need the lower wall superheat, and hence, the boiling is augmented as compared to the increasing process, thus causes the deviation of boiling curves—TD hysteresis.

TD hysteresis depends on the cavity size distribution on the boiling surface and could not be calculated now. Because of the existence of TD hysteresis, the boiling curves may differ from each other for increasing or decreasing heat flux in the region of non-developed nucleate pool boiling. Such inconsistencies are not simply the measurement errors or random variations in the boiling process.

4. QUANTITATIVE DESCRIPTION OF BOILING HYSTERESIS

Boiling hysteresis, a very complex phenomenon, depends on the fluid/surface combinations and is difficult to predict and determine accurately. To describe this phenomenon quantitatively, the following three characteristic parameters are proposed.

4.1. *Temperature overshoot degree* ΔT_{TOS}

TOS hysteresis is characterized by the departure of the wall temperature from the normal boiling curve, causing the temperature overshoot prior to incipient boiling. We consider this temperature difference, ΔT_{TOS}, as a parameter reflecting the degree of departure from the normal boiling curve as shown in Fig. 1, which would be significant in the engineering design of microchip cooling systems and can be used when selecting liquid coolants.

Since we still cannot accurately determine and characterize the boiling surface condition and residual gas volume, the calculation of ΔT_{TOS} can only be conducted by the macro approach, that is, semi-empirical correlation. The incipient boiling superheat at the hysteresis state is

$$\Delta T_{\mathrm{w,i}} = q_{\mathrm{i}}/h_{\mathrm{c}} \tag{7}$$

where q_i is the incipient boiling heat flux; h_c the natural convective heat transfer coefficient.

On the normal boiling curve, the wall superheat can be determined by

$$\Delta T_{\mathrm{w,n}} = c q_{\mathrm{i}}^{n} \tag{8}$$

where, n and c are constants reflecting liquid and vapor properties and surface condition.

Thus the temperature overshoot for boiling hysteresis will be

$$\Delta T_{\mathrm{TOS}} = \Delta T_{\mathrm{w,i}} - \Delta T_{\mathrm{w,n}} = \Delta T_{\mathrm{w,i}} - c q_{\mathrm{i}}^{n}. \tag{9}$$

4.2. *Maximum temperature overshoot degree* $\Delta T_{\mathrm{TOS,max}}$

The maximum temperature overshoot is defined as the temperature difference between the normal wall superheat at boiling incipience, $\Delta T_{\mathrm{w,n}}$, and the incipient wall superheat at the hysteresis state when all cavities on the wall are filled with liquid, i.e. there exists no residual gas.

Consider a conical cavity at the heated wall. Assume a hemispherical bubble of radius r is formed in the cavity at given wall superheat as shown in Fig. 5. The free energy difference for the system can be expressed as

$$\Delta F = \left[\tfrac{4}{3}\pi r^3 \rho_{\mathrm{v}}(g_{\mathrm{v}} - g_{\mathrm{L}}) + 4\pi\sigma r^2\right] f\left(\frac{L}{r}, \beta\right) \tag{10}$$

$f(L/r, \beta)$ has been obtained by Robb [14] as

$$f\left(\frac{L}{r}, \beta\right) = \frac{3}{2}\left[(1-\cos\alpha) + \frac{1}{2}\left(\frac{L}{r}\right)^2 \sin\theta\cos\beta\right] - \frac{1}{2}\left[(1-\cos\alpha)^2(2+\cos\alpha) + \left(\frac{L}{r}\right)^3 \sin\theta\cos\theta\right]. \tag{11}$$

The maximum free energy difference to form a critical bubble of radius r_c will be

$$\Delta F_{\max} = \frac{4}{3}\pi r_{\mathrm{c}}^2 \sigma f\left(\frac{L}{r_{\mathrm{c}}}, \beta\right). \tag{12}$$

The liquid superheat to form this critical bubble can be thus obtained from $\Delta F_{\max}$, i.e.

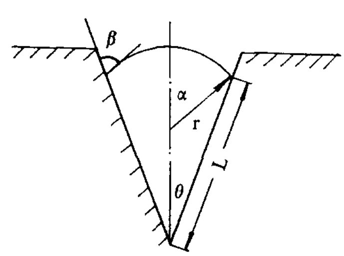

FIG. 5. Bubble formation in a conical cavity.

$$(T_L - T_s)_{max} = \frac{T_s}{\rho_v h_{fg}} \left[\frac{16\pi\sigma^3 f\left(\frac{L}{r_c}, \beta\right)}{3KT_L \ln(n_T KT_L/H)} \right]^{1/2} = (T_L - T_s)_{o,max} \sqrt{\left(f\left(\frac{L}{r_c}, \beta\right)\right)} \quad (13)$$

where K is the Boltzmann constant; H the Planck constant; n_T the molecular number per unit liquid volume; and $(T_L - T_s)_{o,max}$ the liquid superheat to form a critical bubble of r_c in the liquid phase.

Then, the maximum temperature overshoot of hysteresis would be

$$\Delta T_{TOS,max} = (T_L - T_s)_{max} - cq_i^n. \quad (14)$$

For water, if we take $\beta = \pi/3$, $\theta = \pi/6$, the maximum temperature overshoot is about 24°C. Usually, the maximum temperature overshoot is never reached because a certain amount of gas (vapor) is always trapped in the cavities on the wall, but it gives a conservative temperature overshoot limit for the two phase cooling of microelectronic chips.

4.3. *Hysteresis area*

Owing to irregularities of various hysteresis curves, which are located in different temperature ranges for different liquids, the use of the temperature difference is not enough to completely describe the hysteresis characteristics. Therefore, we introduce another parameter—hysteresis area, which is defined as the shaded area enclosed by the normal boiling curve and the hysteresis curve, as shown in Fig. 6.

Assuming that the wall superheat, ΔT, is a function of the heat flux q for both the normal boiling curve and the hysteresis curve, we get $\Delta T_n = f_n(q)$ and $\Delta T_h = f_h(q)$, respectively. The hysteresis area is

$$A = \int_{q_i}^{q_f} [f_h(q) - f_n(q)]\, dq \quad (15)$$

where q_i is the incipient boiling heat flux for normal boiling and q_f the incipient fully-developed boiling heat flux.

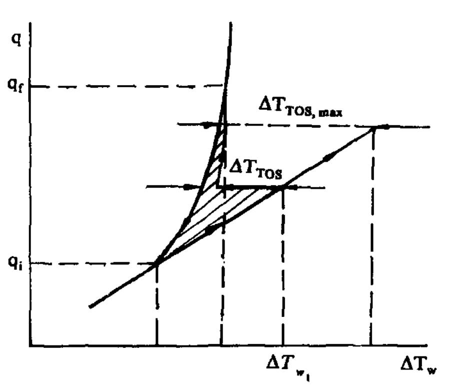

FIG. 6. Hysteresis area.

The hysteresis area can be used to compare the degree of deviation from the normal boiling curve for different fluid/surface systems. The temperature difference for fluorocarbon liquids is far bigger than that of cryogenic liquids. However, it is known that boiling hysteresis of cryogenic liquids is more prominent, which can only be explained by consideration of the hysteresis area. Some typical values of the hysteresis area calculated from the experimental boiling curves are given as follows: distilled water–porous copper surface from ref. [15], $P = 10^5$ Pa, $A = 23.5 \times 10^3$ W m^{-2} K; F-113—stainless steel from ref. [16], $P = 9.8 \times 10^5$ Pa, $A = 4.6 \times 10^3$ W m^{-2} K; liquid hydrogen–stainless steel (rough surface) from ref. [17], $P = 1.22 \times 10^5$ Pa, $A = 0.85 \times 10^3$ W m^{-2} K.

The hysteresis area reflects the uncertainty range of boiling heat transfer data and shows the influence of the boiling hysteresis on the incipient boiling process. One can consider it as a macro effect of surface microstructure. Further consideration would significantly improve our knowledge of the influence of surface condition on boiling heat transfer.

5. CONTROLLING TECHNIQUES FOR ELIMINATING BOILING HYSTERESIS

5.1. *Influence factors*

Boiling hysteresis is a macro phenomenon. It depends on the fluid/surface combination, which is composed of liquid coolant, solid surface and fluid/surface interface characteristics. Factors, such as surface aging, liquid wetting, thermal properties and surface roughness, result in changes for these three aspects and cause different hysteresis phenomena, as seen in equation (6). Therefore, it is expected that various researchers will obtain diverse hysteresis curves.

For porous surfaces, there are great numbers of cavities with different sizes and different trap gas contents, and so, both TOS and TD hysteresis are considerably greater. For smooth surfaces, the cavity numbers are small and the cavity size distribution is nearly uniform, the hysteresis will not be obvious.

It has been found that, using different experimental procedures changes the gas trapped in the surface cavities and causes different hysteresis curves [9, 10]. In addition, liquid subcooling makes some vapor trapped in the cavities condense and increases the hysteresis. Joudi and James [18] observed the incipient boiling characteristics at atmospheric and subatmospheric pressures, and found the temperature overshoot tending to increase with increasing pressure. Many nucleation sites on the surface would be inactive at increased pressures and increase the hysteresis phenomena.

In short, the main factors which influence boiling hysteresis are surface conditions, thermal properties of the liquid coolant and wall, system pressure, the thermal history of the wall and the heating procedure.

5.2. *Possible techniques to eliminate hysteresis*

Possible techniques for eliminating nucleate pool boiling hysteresis have been reviewed in detail in ref. [15]. The most significant techniques are: changing the fluid properties (such as reducing the fluid wetting characteristics and the use of multi-component liquid coolants), changing the surface conditions and the use of supplementary measures. For example, a reentrant cavity will trap more gas; therefore, a heated surface with such cavities will reduce the hysteresis phenomena. Cooper [19] reported that the use of electric fields can eliminate boiling hysteresis.

Shi and Ma [8] have conducted numerous experiments to determine the effect of locally fluidized particles in a liquid pool on boiling hysteresis. The results show that locally fluidized particles can diminish boiling hysteresis, which is promising to direct the application of solid particles in the cooling of electronic equipment.

6. CONCLUDING REMARKS

Hysteresis phenomena, of great importance in boiling heat transfer, can be generalized into two kinds: TOS hysteresis and TD hysteresis. It is believed that the vapor gathering, vapor propagation and covering are the main mechanism of TOS hysteresis, while TD hysteresis is caused by the further vapor propagation of nucleation bubbles.

Three characteristic parameters, temperature overshoot degree, maximum temperature overshoot degree and hysteresis area, are proposed in this work to describe quantitatively the boiling hysteresis phenomenon.

Hysteresis curves vary considerably for pool boiling. The curves can be affected by surface aging, surface roughness, working liquid, experimental procedure, etc.; i.e. anything that affects the fluid/surface combination. Changing the fluid properties and the surface conditions, and the use of supplementary measures, can eliminate or reduce boiling hysteresis. Locally fluidized particles in close vicinity to the heated surface also have a significant effect on boiling hysteresis.

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