INCREASED NUCLEATION SITE FOR BOILING IN MICRO/NANO STRUCTURE
FOR ENHANCED EVAPORATING COOLING

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ABSTRACT
Nucleate boiling is a very efficient way of cooling mechanism in high power density system. Bubble formation in nucleation boiling phenomenon above critical heat flux in micro and nano channels may lead to instability of the flow in one direction and dry out condition. This paper reviews the process for increased nucleate boiling in micro and nano structure for enhanced evaporating cooling. Surface characteristics, wettability, electric field, vibration along with variation of surfactant, pressure and velocity taken into consideration as well. Microstructure plays an important role in enhancement of the nucleate boiling heat transfer mainly by increasing heat transfer area, active nucleation site density and bubble departure frequency. Groove structure on the heating surface has not been prioritized in the past so much more attention is needed in finding the proper structure for increasing the nucleate boiling.

INTRODUCTION
When surface temperature is greater than the saturated fluid temperature, the boiling is referred to as nucleate boiling but under this condition still the boiling curve remains below the critical heat flux (CHF) point (boiling curve for water at 1 atmosphere pressure) as shown in [1]. The peak of the curve for nucleate boiling will be CHF after which transitional boiling will occur. Nucleation temperatures basically depend upon the surface temperature but not only related to the higher temperature.
Basically, two types of nucleation occurs namely homogeneous nucleation and heterogeneous nucleation [2]. Homogeneous nucleation occurs within the liquid and the heterogeneous nucleation which occurs at the solid-liquid interface. Heterogeneous nucleation in general requires less heat flux than homogeneous nucleation.
For nucleation site boiling in micro/nano channels mostly heterogeneous nucleation is taken in consideration. Heterogeneous nucleation is the function of the contact angle between the vapor and the solid surface.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>θ</td>
<td>[°]</td>
<td>Liquid contact angle</td>
</tr>
<tr>
<td>β</td>
<td>[°]</td>
<td>Half cavity cone angle</td>
</tr>
<tr>
<td>T</td>
<td>[K]</td>
<td>Temperature</td>
</tr>
<tr>
<td>rc</td>
<td>[m]</td>
<td>Radius of active site</td>
</tr>
<tr>
<td>ΔT</td>
<td>[K]</td>
<td>Wall superheat, ΔT=T_W-T_L</td>
</tr>
<tr>
<td>δT</td>
<td>[m]</td>
<td>Thickness of thermal boundary layer</td>
</tr>
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</table>

To understand the boiling nucleation the conditions to be familiar with for the heated surface are:
- Geometrical characteristics of the cavity for boiling
- Density of the boiling sites on the surface
- Effect of wetting angle hysteresis on nucleate boiling

The activity of nucleate boiling depends upon capability of maintaining residual vapor bubble which will become seed for the next one. There are two mechanism involved in retaining the residual vapor bubble. Phenomenological approach which depends on boiling cavity geometry and thermodynamic approach involve modeling of the process [1].

Commonly in order to reduce the wall or surface temperature flow velocity is increased so that convective heat transfer rate is higher. Nucleate boiling has some advantages like it requires less pumping power and promisingly it removes heat more efficiently from the hotter surface than the cooler one thus offers the potential to achieve uniform temperature distribution throughout the structure. Various studies related to the surface characteristics, composition of liquid, surfactant addition, along with application of pressure, vibration, electric field, and velocity were carried out. Important parameters for consideration in order to enhance CHF are surface geometry, spread ability and wettability. Moreover, nano fluids, as a class of nanotechnology based fluid, consist of base fluids (e.g. water, oil, bio-fluids etc.) with various particles (e.g. copper, gold, silver, metal-oxides etc.). It has attracted great interest because of their highly enhanced thermal conductivity at low nanoparticle concentration [3-10]. The effect of nano fluids to boiling/evaporation heat transfer is an ongoing topic of research.
\[ \sigma \quad [N/m] \quad \text{Liquid surface tension} \\
\rho \quad [kg/m^3] \quad \text{Density} \\
h_f \quad [J/kg] \quad \text{Liquid latent heat} \\
\delta_m \quad [m] \quad \text{Thickness of the liquid microlayer} \\

\begin{align*}
\delta & \quad \text{Thicknes of thermal boundary layer} \\
\beta & \quad \text{Cone angle} \\
\theta & \quad \text{Possible geometric size} \\
T_{max} & \quad \text{Maximum} \\
T_{min} & \quad \text{Minimum} \\

\hline
\text{Subscripts} \quad & \text{Bulk Liquid} \\
\infty & \text{The heater wall} \\
s & \text{Saturation} \\
v & \text{Vapor phase} \\
\text{max} & \text{Maximum} \\
\min & \text{Minimum} \\
\end{align*}

LITERATURE REVIEW

As referred to in the introduction part, the nucleation boiling is a useful way for cooling some components to avoid the excess temperature, which is attracting more and more researchers. Some important methods for enhancing nucleate boiling heat transfer have been carried out, such as surface morphology, electric field, composition of working liquid, orientation of the heated surface, vibration etc.

Surface Morphology

It is generally agreed on that the surface characteristics (irregularities or microstructures) can excite a small amount of vapor to generate activated nucleation sites when a heat flux is imposed. And only the certain size and geometric shape surface microstructures can be "activated" to develop into active sites.

Bankoff used a conical cavity hypothesis to reveal the liquid contact angle on the heater surface relative to the cavity cone angle to check whether it can trap the vapor to generate the nucleate sites [11]. As shown in Figure 1, the cavity can be excited to an active nucleation site only when the liquid contact angle (\( \theta \)) is bigger than the cavity cone angle (2\( \beta \)), or it will flow together with the liquid, i.e. the possible geometric size need to satisfy the relation that follows:

\[ \theta > 2\beta \quad (1) \]

In addition, the cavity mouth size is also an important factor for whether the cavity could be activated. Chi et al. indicated that only the cavity mouth size within a certain range can be excited, which depend on the thermal boundary, the heat source temperature, the liquid surface tension and the bulk pressure [12]. Hsu et al. pointed out that for a liquid with a bulk temperature \( T_\infty \) heated by a constant wall superheat \( \Delta T \), the mouth radius of cavities are correlated to the liquid properties as

\[ r_{max,min} = \frac{2\delta_T(T_w - T)}{2C_1(T_w - T_{\infty})} \left( 1 + \left( 1 - \frac{8C_2\sigma T(T - T_{\infty})}{h_f\rho v\delta_m(T_w - T)^2} \right)^{1/2} \right) \quad (2) \]

Where \( \delta_T \) is the thickness of thermal boundary layer, \( C_1 \) and \( C_2 \) are the constants respectively [13]. The equations (1) and (2) show the geometry and size of the surface microstructures for enabling the generation of bubble nucleation. However, the distribution functions of the different cavity and cone angle are different for different heated surfaces. For instance, Yang and Kim measured the cavities on a stainless steel heat source. They found that cavity mouth size was in accordance with Poisson distribution, the cone angle being of normal distribution [14]. Qi et al. also showed that the morphologies of an SS and a brass surface are different distributions for cavity mouth and cone angle [15]. That means for different surface morphology, even for a specified liquid boiling on heaters with the same wall superheat, the nucleation site density could be different per unit surface area because of the different probability density functions.

\[ \text{Figure 1 Cavity cone} \]

In addition, the wettability also has a significant effect on bubble nucleation. Qi et al. showed that the nucleation site density decreases though the surface wettability (contact angle) increases [15]. Basu et al. found that the excited nucleation site density is lower in liquid with \( \theta =30^\circ \) than that in liquid with \( \theta =90^\circ \) for the same heater with 12 K wall superheat, which is consistent with the result from Qi [15-16].

Yu-Tong Mu [17] compared the numerical behavior for nucleation on roughened surface based on phase change lattice Boltzmann method without any artificial disturbance and the results agree with experimental data from Shojaein and Kosar (2015). Table I shows the comparison of different types of grooves including triangular, circular, rectangular and trapezoidal shaped grooves [18-21]. From which we can easily find that only triangular shaped groove has a smaller amount of vapor exists compared with others. In addition, for both triangular and circular grooves, a lower heat flux distribution has a much flatter distribution than that of rectangular and trapezoidal shaped grooves.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
Triangular groove & Circular groove & Rectangular groove & Trapezoidal groove \\
\hline
Small amount of vapor exists & Large amount of vapor is & Large amount of vapor is & Large amount of vapor is \\
in groove & trapped & trapped & trapped \\
\hline
Relatively low bubble & Bubble release & ----- & ----- \\
release frequency & frequency is higher & & \\
\hline
\end{tabular}
\caption{Comparison of different types of grooves}
\end{table}
from the discussion above, we can find that the surface morphology and the contact angle are the main factors determining the properties of bubble nucleation, and thus related to the critical heat flux.

**Electric Field**

The importance of Electro hydrodynamics (EHD) enhancement of heat transfer on boiling process has been widely recognized by researchers in recent years. Not only the maximum heat flux and bubble frequency will increase, but the bubble size will decrease as well by adjusting the electric filed during the boiling process. Particularly, there are more small sized bubbles generated from the heat surface by applying a non-uniform electric field, by which the heat flux will increase because of the mutual interactions among a bulk liquid, vapor bubbles and electric field.

For instance, in order to reveal the effects of an electric field on enhancing nucleate boiling heat transfer and know about bubble dynamic behavior, Kweon et al. did the measurements including the onset of nucleate boiling and CHF to illustrate the boiling curve under saturated pool boiling [22]. They used a thin wire to ensure a large gradient electric field at the surface of the wire, which can generate a very strong electric field. When there is no electric field buoyancy force exceed the surface tension force and bubbles depart. But with the application of electric field, theoretically both electric charge and polarization forces act on the bubble.

The comparison of effects for different electric field applied for the pool boiling is shown in Figure 2, which gives a clear picture of the boiling curves shifted to lower wire temperature and the significant increase of the heat flux (5, 10 and 15 kV dc voltages applied, separately) [22]. It is easy to see that about 3.5 times increased for 15 kV DC voltage applied at 75°C compared with the case in which the electric field is absent. In addition, the non-uniform electric field can change the bubble dynamic behavior. Khanlou et al. indicated that the main effect is EHD boiling, which plays a key role in this bubble behaviors with the applied voltage increasing, rather than the electro-convection effect, though both of them can increase the CHF [23].

On the application of the non-uniform electric field electro convective flow is generated around the heating wire. Choi (1962), Lovenguth (1958), Carrica et. al. (1995), Kwenon (2000) have good agreement on the work done on CHF in non-uniform DC electric field. It was shown that the electro convective flow plays a key role in determining the ONB heat flux. Most study have shown that after applying electric field the heat transfer enhancement is by a factor of 2 to 6 but some of the study have even shows the enhancement up to a factor of 60 [24-25].

![Figure 2](image.png)

**Binary Mixture**

Two or more fluids mix together can change the heat transfer coefficients (HTC) compared with a pure fluid. That is because, for instance a pure liquid, will simply evaporate at the liquid-vapor interface. However, the more volatile component will evaporate at the liquid-vapor interface into a vapor bubble of the more volatile component when two fluids are mixed together. This case will make the liquid-vapor interface depleted in the more volatile component. And the molecules of that diffuse to the interface and evaporate to satisfy further evaporation. It has been verified through experiments by Robinson that the HTC with pure water is larger than that with 50-50 water antifreeze mixture [25-26].

Inoue et al. studied the HTC of the nucleate pooling boiling on horizontal platinum wire with the binary mixture of R12+R113, R22+R113 and so on in the range of 2-8 bar pressure under a constant heat flux [27]. They found that the HTC for the mixtures is smaller than that in the single component substance. One interesting thing is that they found the HTC depending on the system pressure in the single component more extensively than that in liquid mixture. The equation of HTC calculation was put forward within an accuracy of ±20% for the existing mixtures with a small difference in saturation temperatures (however, the accuracy was ±25% for a large difference).

Hence, how to calculate the HTC more accurately is a challenge. A proper theoretical model to calculate nucleate boiling HTC of binary mixtures is very important. Many researchers are focusing on the single bubble model in recent two decades. The micro region (a tiny thin film area, which shown in Figure 3) model was constructed in a macroscopic vapor bubble growth model by several researchers using different assumptions and simplifications in order to calculate the nucleate boiling HTC of the pure substances [28-33]. Kern et al. also used a single bubble model to analyze the HTC on the micro and macro areas.
nucleate boiling of binary mixture still needs to be developed in the future. Although it is a hot topic for the HTC studied by many researchers on binary mixture, a general agreement about the dominant effect of the different physical phenomenon on nucleate boiling of binary mixture still needs to be developed in the future.

They got that the microscale heat and mass transfer phenomena has a more significant influence on the HTC compared with that in macroscale. Variations of pressure and velocity are the conventional way of increasing the heat flux in the liquid but due to the advantages of the other methods these are not preferred for researches recently.

**DISCUSSION AND CONCLUSION**

Based upon the various studies on the improvement of nucleate boiling it is found out that surface morphology, electric field, doping in the liquid, vibration etc. play an important role. It reflects that nucleate boiling has clearly higher potential than the conventional boiling but the progression from nucleate boiling to the transitional boiling and film boiling needs to be avoided.

From the literature and previous findings each model proposed by the researchers for surface morphology has some key assumptions to develop the correlation. But the primary dependence parameter in case of the morphology is the contact angle between the solid surface and the liquid, relating to the wettability of the liquid on the solid surface. Microstructure plays an important role in enhancement of the nucleate boiling heat transfer mainly by increasing heat transfer area, active nucleation site density and bubble departure frequency. Groove structure on the heating surface has not been prioritized in the past so much, more attention is needed in finding the proper structure for enhancing the nucleate boiling.

Wettability change during Nano fluid boiling shows significant heat transfer enhancement especially of the CHF but the prediction of HTC is not in a comprehensive step. Thus, a further study on wettability effect is required with integrated consideration of CHF and HTC together under different experimental conditions. Nano fluids work with the same principle as the variation of the contact angle between the heating surface and the liquid. The Nano materials play a vital role for the improvement of the nucleate boiling. Flow boiling with Nano fluids does not shows a promising CHF enhancement and most of the researches focused on the use of particular material only (Al2O3). Very few other Nano materials were tested for the experiment. So more experiments and researches need to be performed on different nano particles with different Nano material concentration. Further study on the effect of pressure and heater geometry is required as well.

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Vibration has the main effect that large bubbles can be broken into smaller which decreases the nucleation density and similarly binary mixtures basically increase the CHF than the pure liquid alone due to the different heat capacity.

To the best of the author’s knowledge, the effect caused by EHD experimentally from the researches is that the bubble is elongated in the direction of the electric field. But the prediction of their magnitude and influence on the mechanism of the boiling is still unclear. It therefore needs further investigation. The mechanism, which leads the process for breaking into smaller bubbles from a large bubble, is still unclear and thus needs to be find out.

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