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# Energy-Efficient Technology Based on Nucleate Boiling Heat Transfer

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**Abstract:** ***The demand for energy-efficient technologies has increased dramatically in recent years. As a high efficient heat transfer mode, nucleate boiling has been widely used in a variety of engineering fields including electronic device cooling, thermal power plant, refrigeration, etc. The trend of the scientific research on nucleate boiling heat transfer is first reviewed. Then nonlinear dynamics based on chaos and fractal theories is introduced to investigate the underlying mechanism of nucleate boiling heat transfer. In the last part, the concept of Shannon entropy is introduced and its potential to qualitatively measure the randomness of the solid boiling surface is discussed.***

**Keyword:** Energy-efficient technology; Nucleate boiling; Nonlinear dynamics; Shannon Entropy

## 1. Introduction

Nowadays, the need of miniaturization and integration of electronic elements result in the increase of power density [1]. Conventional cooling technologies based on single phase liquid become not qualified in many industries. The heat transfer method based on liquid to vapor phase change has outperformed the conventional methods in many aspects. Nucleate boiling heat transfer is a representative one in phase-change-based thermal technology and it has been widely used in engineering. The microscopic structure of the boiling surface plays an important role in the thermal performance of the boiling heat transfer. In most cases, the cavities with vapor or gas inside serve as nucleation sites to generate bubbles. The thermal transport is upper bounded by critical heat flux (CHF) where the state of boiling change from nucleate boiling to film boiling. The CHF can be increased by adding a porous layer coating on a solid heater surface, and this kind of coating can be realized by welding, sintering, or particle brazing [2]. The enhancement of heat transfer in nucleate boiling has been experimentally achieved by use of porous graphene/carbon nanotube hybrid surface, and SEM (Scanning Electron Microscopy) was used in the experiment to observe the deposition of the nanoparticles [3]. The heat transfer enhancement methods in nucleate boiling can be classified into active and passive methods. Passive methods usually used include modified surfaces, porous surfaces, and addition of nanoparticles to the fluid, and active methods usually employed include adding external electrostatic field and fluid vibration [4]. The ideal heating surface is such surface that the wall superheat (the temperature difference between the surface and the liquid ) does not change with the heat flux, and the constancy of the wall superheat needs the continuous generation of the bubbles, which requires the remaining of some vapour at the nucleation site after the bubble detachment and possibly long three-phase-line [5]. Monte Carlo method was used to construct a model to describe the interaction between nucleation sites in boiling heat transfer [6]. The technology of liquid crystal thermograph was used to obtain the wall temperature field in nucleate boiling and an approach using non-orthogonal empirical functions was employed to identify the nucleation sites on the heated wall [7]. It was shown that the synchronization of the process of bubbles departure can be realized with the analysis of the correlation between the wavelet spectrums of the temperature-time series under two cavities on the heater surface [8]. A mechanistic model based on the interfacial area transport equation was provided to enhance the analysis capability of two-phase flows under the condition of subcooled boiling [9]. The variation of the thermal transport between the bubble and the surrounding liquid heavily depends on the flow condition, and the closure relations for bubble departure and lift-off diameters are very important for the heat transfer models of multiphase flow with boiling [10]. The thickness of the initial microlayer decreases with the increase of the boiling wall superheat, and a dynamic microlayer model was proposed to predict the critical heat flux [11]. The experimental investigation of nucleate pool boiling of nonazeotrope mixture HFC-32/134a and azeotrope mixture HFC-32/125 was carried out and it was found that the accuracy of the prediction of the heat transfer coefficient depending on the current correlations varied considerably with mixtures and heat flux [12]. Nonlinear analysis of the time-series data of the temperature fluctuation under the nucleation site was conducted, and it was shown that low dimensional deterministic chaos emerged during the nucleate boiling process [13]. A fractal model to describe subcooled flow boiling is proposed, and the model incorporated the influence of the parameters including the fractal distribution of nucleation sites, the heated wall superheat, liquid subcooling, Reynolds number of the fluid, the fractal dimension, the cavity size, the contact angle and the physical properties of fluid on the subcooled flow boiling [14]. Based on the fractal and statistical theories to depict the porous structure of the deposits, a novel approach is developed to predict the influence of the thermal behaviour of fouling in steam generators, and in this method accounts the heat transfer was driven by the liquid-vapor phase change [15]. The bubbles generated in nucleate boiling are shown in Figure 1.

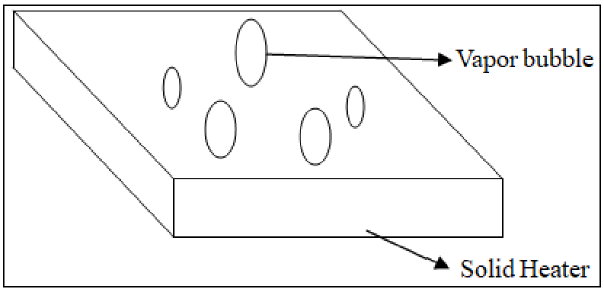


**Figure 1:** Bubbles generated in nucleate boiling heat transfer

## 2. The application of nonlinear dynamics in investigating nucleate boiling heat transfer

Most nonlinear dynamic systems have the nature of deterministic chaos, and most of dynamical systems encountered in engineering are nonlinear dynamics systems, such as fluid flow, heat transfer, combustion, etc. The hallmark of deterministic chaos is the sensitivity to the initial conditions. Nonlinear time-series analysis has been widely applied to investigate nonlinear dynamic systems such nucleate pool boiling system. The time series data of the temperature under the nucleation sites gives the information of the behavior of the bubbles, which is linked to the physical process of the liquid-vapor phase change. Takens's theorem is often used to reconstruct an attractor [8] of a time-series data.

The correlation sum for a collection of points $X_n$ in vector space is defined as the following:

$$C(\varepsilon)=\frac{2}{N(N-1)}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\Theta(\varepsilon-\|X_i-X_j\|) \quad (1)$$

where $C(\varepsilon)$ is the correlation sum, and $\Theta$ is Heaviside function defined as

$$\Theta(x)=\begin{cases}1 & if \quad x>0\\ 0 & if \quad x\le 0\end{cases} \quad (2)$$

To get the value of $C(\varepsilon)$, we need to calculate the number of the pairs of points that satisfy the condition that the distance between the pair points is smaller than a given distance $\varepsilon$ in the embedding vector space. Fractal structure exists if there is the relationship between $C(\varepsilon)$ and $\varepsilon$ obeys the power law:

$$C(\varepsilon)\approx\varepsilon^D \quad (3)$$

where $D$ is the fractal dimension, which measures the structure of the attractor.

## 3. Qualitative measure of the boiling surface structure based on Shannon entropy

To measure the microstructure of a solid boiling surface, X-Z profiles [16] are used and they are often obtained by microscope through scanning the surface. For a X-Z profile, X and Z denote the horizontal and vertical directions respectively. The Z-direction data represent the depth of the point on the boiling surface. The X-direction data can be used to calculate the diameter of the cavity.

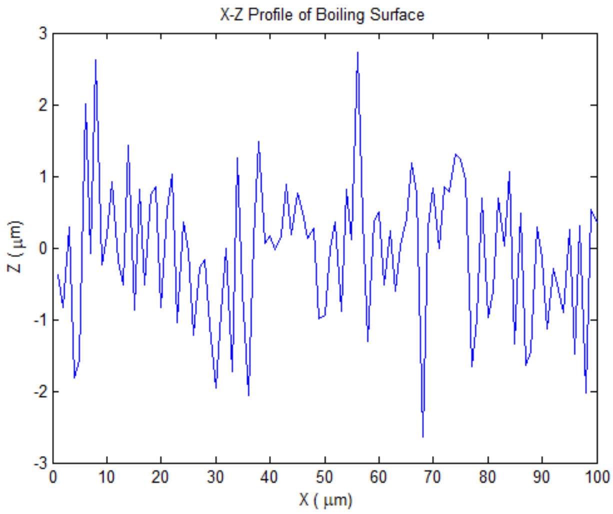


**Figure 2:** X-Z profile of boiling surface

Shannon entropy [17-20] serves as a parameter to qualitatively measure the randomness of a signal. It is defined as the following

$$H=-\sum_i p_i\cdot\log_2 p_i=\sum_i p_i\cdot\log_2\frac{1}{p_i} \quad (4)$$

where $H$ is the Shannon entropy of the discrete signal , $p_i$ is the probability of the $i$ th possible value of the discrete signal. The data of the X-Z profiles can be plugged in to eq(4) to calculate the boiling surface entropy to measure the randomness of the boiling surface structure. The less is the probability of an event the larger is the information the event brings to the observer (information receiver). A special case is that if the probability of an event is 1 (100%), it means that the event is certainly to happen and it brings no information the observer.

## 4. Conclusions

As a high efficient heat transfer mode, nucleate boiling heat transfer shows strong nonlinear behavior. In the complex system of nucleate boiling, it includes heat transfer between bubble and the solid heating surface, phase change, bubble motion, the liquid flow around the bubble, and etc. Nonlinear dynamics paves the way to qualitatively measure the complex behavior in the nucleate boiling process. A novel concept name boiling surface entropy is proposed and it serves as a parameter to conduct qualitative measure of the randomness of the boiling surface microstructure.

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