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Technical Note

# Dry patch interaction caused by lateral conduction in transition boiling

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**Abstract**

The present paper analyzed the temperature fluctuation correlation caused by lateral heat conduction in heater in transition boiling system and derived the critical temperature fluctuation space correlation length, within which dry patches might interact to result in the occurrence of stable film boiling regime. The mechanism for non-hydrodynamic transition was revealed. The present investigation not only provided comprehensive and rational insights on transition boiling mechanisms, but also might find important industrial applications. © 2001 Elsevier Science Ltd. All rights reserved.

*Keywords:* Transition boiling; Film boiling; Dry patch; Temperature fluctuation correlation

## 1. Introduction

Transition boiling is encountered in a number of applications, including metallurgical quenching processes, immersion cooling of high temperature components and nuclear reactors, etc. Research on transition boiling will also lead to a broad understanding on nucleation and film boiling. Although having been studied for decades, transition boiling still holds its place as the least understood of the several boiling mechanisms [1]. This can be attributed to two reasons: (a) the complexity of transition boiling heat transfer phenomena, and (b) the difficulty of performing transition boiling experiments. Since the pioneering work of Berenson [2], researches found that transition boiling has salient features such as the direct liquid–solid contact, strong effect of the wall temperature characteristic and catastrophe, and hysteresis, etc. In transition boiling regime, the number and size of the dry patch increase [3]. The formation, growth and being re-wetted of dry patches may provide the key to the understanding of heat transfer mechanism. The occurrence of burnout is directly related to the fact that whether the dry patches can be re-wetted or not.

Witte and Lienhard [4] and Ramilison and Lienhard [5] reported the occurrence of sudden "jumps" between nucleate boiling and film boiling regimes. Large dry patches once emerged, would flush and cover the entire heated surface. These observations correlated with the hysteresis characteristics of a multiple steady-state dynamic system. Two transition boiling curves were commonly observed in a heat-flux controlled experiment, referring, respectively, to as the film-transition and nucleate-transition boiling curves [4]. Conventionally the occurrence of two transition boiling curves was attributed to the difference in advancing and receding contact angles.

In fact, there is yet no consensus as to mechanism and condition for the occurrence of catastrophe and hysteresis in transition boiling [6]. Furthermore, the available models were developed by averaged procedure.

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**Nomenclature**

| | |
|---|---|
| $a$ | thermal diffusivity ($m^2$ $s^{-1}$) |
| $c$ | solid specific heat (J $K^{-1}$ $kg^{-1}$) |
| $h$ | heat transfer coefficient (W $K^{-1}$ $m^{-2}$) |
| $l$ | correlation length (m) |
| $q$ | heat flux (W $m^{-2}$) |
| $r$ | radial coordinate (m) |
| $t$ | time (s) |
| $T$ | temperature (°C) |
| $x$ | $x$-coordinate (m) |
| *Greek symbols* | |
| $\Delta T$ | liquid superheat (°C) |
| $\rho$ | density (kg $m^{-3}$) |
| $\lambda$ | thermal conductivity (W $m^{-1}$ $K^{-1}$) |
| $\delta$ | wall thickness (m) |
| *Subscripts* | |
| c | critical |
| d | diffusion |
| f | fluctuation |
| s | saturation |
| 0 | reference state |

However, for actual transition boiling, the wall temperature is extremely non-uniform for the stochastic formation of dry patches. Dynamic feature might be masked by averaged procedure [7]. The studies on dry patches may lead to a broad and thorough understanding on transition boiling.

Non-linear interaction system can produce catastrophe phenomena, i.e., non-equilibrium phase transition, which can be explained that system will change from one kind of macroscopic state to another macroscopic state by fluctuation correlation and cooperative effect. In this case, not only external feature will change, but also underlying symmetry will change. Catastrophe phenomenon in boiling system virtually corresponds to non-equilibrium phase transition and transition of boiling regimes may be realized by temperature fluctuation correlation caused by lateral heat conduction in heating wall.

The present paper analyzed the temperature fluctuation correlation caused by lateral heat conduction in heater and derived the critical correlation length. The transition boiling behavior was correspondingly investigated. The possible way to avoid or minimize the unstable transition boiling regime was then provided.

## 2. Temperature fluctuation correlation in transition boiling

Consider the dry patches randomly distributed in transition boiling system, as shown in Fig. 1.

Assuming the average undisturbed temperatures at different positions $r$ and $r'$ on heater are equal, i.e.,

$$\langle T(r)\rangle = \langle T(r')\rangle = T_0 \qquad (1)$$

for the non-uniformity and stochastic performance of boiling process, the temperature at $r'$ will be affected by 'field' produced by the temperature variation at $r$ for the random formation, growth and rewetting of dry patches, which will result in the temperature at $r'$ to be different from the temperature at $r$. Simultaneously, the temperature at $r$ can be also affected by the temperature fluctuation at $r'$.

Temperature fluctuation correlation at different positions can be defined and calculated as

$$\begin{aligned}\langle \delta T(r)\delta T(r')\rangle &= \langle [T(r) - \langle T(r)\rangle][T(r') - \langle T(r')\rangle]\rangle \\ &= \langle T(r)T(r')\rangle - T_0^2 \qquad (2)\end{aligned}$$

If the temperature distribution at $r'$ has no relation with the temperature distribution at $r$, we have

$$\langle T(r)T(r')\rangle = \langle T(r)\rangle\langle T(r')\rangle = T_0^2. \qquad (3)$$

So $\langle \delta T(r)\delta T(r')\rangle = 0$.

Generally, the temperature distribution at $r'$ will be influenced by the temperature distribution at $r$, $\langle \delta T(r)\delta T(r')\rangle$ will then be not equal to 0. Therefore, $\langle \delta T(r)\delta T(r')\rangle$ can be considered as the quantity of space correlation and can be also named space correlation function, which is the function of positions of two points. If space correlation is significant when $l < l_c$, while space correlation can be ignored when $l > l_c$, then $l_c$ is called space correlation length [8], which can reflect

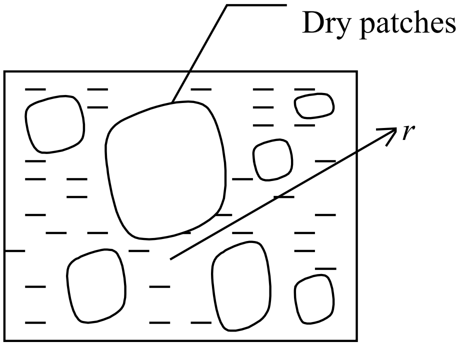

Fig. 1. Dry patches randomly distributed in transition boiling system.

the interaction behavior from macroscopic and microscopic views.

For simplicity, considering the physical model as the one-dimensional problem shown in Fig. 2, the equation in controlling the heat transfer in the plate can be written as

$$\frac{\partial T}{\partial t} = -\frac{h}{\rho c \delta}(T - T_{\mathrm{s}}) + \frac{q}{\rho c} + a\frac{\partial^2 T}{\partial x^2}, \tag{4}$$

where $T$ is temperature in the plate, $t$ is time, $\rho$ is plate material density, $a$ is thermal diffusivity of plate material, is plate thickness, $c$ is specific heat of plate, $h$ is heat transfer coefficient, $T_{\mathrm{s}}$ is liquid saturation temperature and $q$ heat source in the plate.

The first term and the second term in right-hand side of Eq. (4) can be considered as the contribution of source to the temperature $T$ and written as

$$f(T) = -\frac{h}{\rho c \delta}(T - T_{\mathrm{s}}) + \frac{q}{\rho c}. \tag{5}$$

Eq. (4) is written as

$$\frac{\partial T}{\partial t} = f(T) + a\frac{\partial^2 T}{\partial x^2}. \tag{6}$$

The effect of fluctuation is ignored in Eq. (6). To analyze the correlation, it is necessary to include the fluctuation effect (it is more important at the transition critical point). Both the source term and diffusion term can fluctuate. The detailed analysis is as follows.

For the fluctuation of diffusion term, we have

$$\langle \xi_{d,i}(x,t) \rangle = 0, \tag{7}$$

$$\langle \xi_{d,i}(x,t)\xi_{d,j}(x',t') \rangle = K_d(x,t)\delta_{i,j}\delta(x-x')\delta(t-t'), \tag{8}$$

$$\begin{aligned}&\langle \nabla \cdot \xi_{d,i}(x,t) \nabla \cdot \xi_{d,j}(x',t') \rangle \\ &\quad = \nabla \cdot \nabla'[K_d(x,t)\delta_{i,j}\delta(x-x')\delta(t-t')].\end{aligned} \tag{9}$$

For the fluctuation of source term, we have

$$\langle \xi_{f,i}(x,t) \rangle = 0, \tag{10}$$

$$\langle \xi_{f,i}(x,t)\xi_{f,j}(x',t') \rangle = K_{f,ij}(x,t)\delta_{i,j}\delta(x-x')\delta(t-t'). \tag{11}$$

The stochastic differential equation including the fluctuation effects can be written as

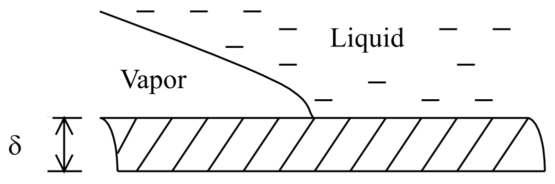

Fig. 2. Analytical model.

$$\frac{\partial T}{\partial t} = f(T) + a\frac{\partial^2 T}{\partial x^2} + w(x,t), \tag{12}$$

where

$$\begin{aligned}\langle w_i(x,t)w_j(x',t') \rangle = \{&K_{f,ij}(x,t)\delta(x-x') \\ &+ \nabla \cdot \nabla'[K_d(x,t)\delta(x-x')\delta_{ij}]\}\delta(t-t').\end{aligned} \tag{13}$$

Above equation includes two unknown coefficients $K_{f,ij}(x,t)$ and $K_d(x,t)$. To determine the two unknown coefficients, linearized stochastic differential equation corresponding to Eq. (13) is needed

$$\begin{aligned}\frac{\partial \delta T_i(x,t)}{\partial t} &= f'(\{\langle T_j \rangle\})\delta T_i(x,t) + a_i\frac{\partial^2 \delta T_i(x,t)}{\partial x^2} \\ &\quad + \eta_i(x,t),\end{aligned} \tag{14}$$

where

$$\langle \eta_i(x,t) \rangle = 0, \tag{15}$$

$$\begin{aligned}\langle \eta_i(x,t)\eta_j(x',t') \rangle = \{&2\delta_{ij}\nabla' \cdot \nabla[a_i\langle T_i \rangle \delta(x-x')] \\ &+ \delta(x-x')Q_{ij}(\{\langle T_j \rangle\})\}\delta(t-t'),\end{aligned} \tag{16}$$

where

$$\delta T_i(x,t) = T_i(x,t) - \langle T_i \rangle, \tag{17}$$

$$f'(\{\langle T_j \rangle\}) = \partial f(\{\langle T_j \rangle\})/\partial \langle T_j \rangle. \tag{18}$$

The present model is one-dimensional. Introducing Eq. (5), Eqs. (14)–(16) can be changed

$$\frac{\partial \delta T(x,t)}{\partial t} = -\frac{h}{\rho c \delta}\delta T(x,t) + a\frac{\partial^2 \delta T(x,t)}{\partial x^2} + \eta(x,t), \tag{19}$$

$$\langle \eta(x,t) \rangle = 0, \tag{20}$$

$$\begin{aligned}\langle \eta(x,t)\eta(x',t') \rangle = &\left[\frac{h}{\rho c \delta}\langle T(x,t) \rangle + \frac{q}{\rho c}\right]\delta(x-x') \\ &+ 2a\nabla' \cdot \nabla[\langle T(x,t) \rangle \delta(t-t')].\end{aligned} \tag{21}$$

Fourier and inverse Fourier transformations are applied to Eqs. (19) and (21) to yield the space correlation length [9]

$$l_{\mathrm{c}} = \left|\frac{a}{f'(T)}\right|^{1/2} = \left|\frac{\lambda \delta}{h}\right|^{1/2}. \tag{22}$$

Therefore, for given heater the transition boiling heat transfer coefficient is in the form of

$$h \propto \frac{1}{l_{\mathrm{c}}^2}, \tag{23}$$

which implies that the temperature will greatly influence the transition boiling heat transfer coefficient. The larger the correlation length, the smaller the heat transfer coefficient will be.

## 3. Results and discussions

### 3.1. Transition to stable film boiling

In terms of Eq. (22), for given heating wall, heat transfer coefficient is the only factor that controls temperature fluctuation space correlation. Therefore, heat transfer coefficient is the only factor that controls the regimes transition to stable film boiling. Temperature fluctuation space correlation length is proportional to $h^{-1/2}$. The correlation length can be very large when $h$ is relatively small and long-distance cooperative effect will thus work, which will result in the change of boiling behaviors and transition of boiling modes.

As shown in Fig. 3, on transition boiling curve, the heat transfer coefficient will decrease with increasing superheat. On the other hand, the density of dry patch number will increase with increasing superheat, which means that the distance between dry patches will decrease with increasing superheat. Sudden transition to film boiling will take place when curve reaches point $A$ where heat transfer coefficient is decreased to let the critical space correlation length be larger than the distance between dry patches. This kind of transition is controlled by non-hydrodynamic effect, and far different from point $B$, which is only controlled by hydrodynamic effect. Really, depending on the actual conditions, the critical space correlation length may range from several millimeters to ten or tens of millimeters, which can often be larger than the distance between dry patches. In fact, many experimental observations support the fact: stable film boiling is often pre-induced before the occurrence of minimum heat flux predicted by hydrodynamic aspects, the transition would often tend to behave like a sudden "jump" [4–6].

### 3.2. The control of unstable transition boiling regime

Transition boiling is an unstable regime where the heat flux decreases with increasing wall superheat, which had better be avoided or to some extend be reduced in many fields such as cooling of electronic components where heat flux must be removed at a great level with a certain temperature limit, chemical–petrol–chemical equipment where processes stability must be accurately controlled, and some other metallurgical processes.

As shown in Eq. (22), the temperature fluctuation correlation length $l_c$ will decrease with increasing heat transfer coefficient $h$. It is expected that temperature fluctuation correlation can be reduced by increasing the transition boiling coefficient. The heat transfer mechanisms in transition boiling regimes are controlled primarily by the convective phenomena in the over-riding liquid layer, hence flow velocity and liquid sub-cooling degree can have a distinct effect on transition boiling heat transfer. The transition boiling curve (or heat transfer coefficient) can be dramatically altered by high flow velocity and liquid sub-cooling degree. On the other hand, the effects of flow velocity and liquid sub-cooling degree on nucleate boiling and critical heat flux are of only limited significance for the intense bubble action is relatively insensitive to motion and liquid temperature [10]. Assuming that $l_c$ is certain for given boiling system, $h_c$ is also determined by Eq. (22), up to which the transition to stable film boiling will be induced, for example point 1 in Fig. 4. As shown in Fig. 4, by increasing flow velocity and sub-cooling degree, the heat transfer coefficients level for transition boiling regime will correspondingly increase, the transition points will then move upward to $2, 3, \ldots$ along the line with gradient $h_{1c}$

$$h_{1c} = q_1/\Delta T_1. \qquad (24)$$

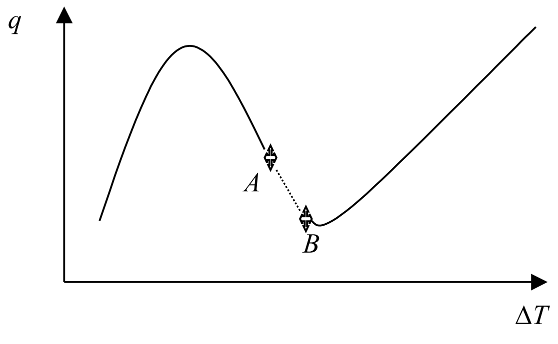

Fig. 3. "Jump" in transition boiling curve.

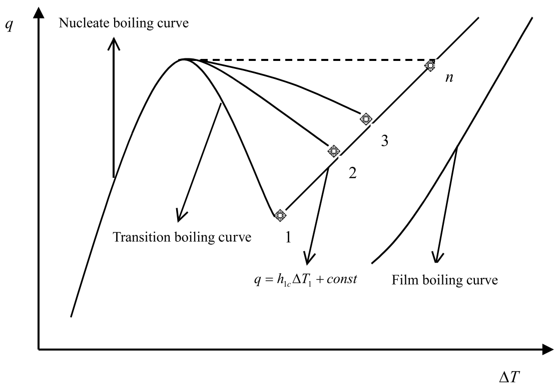

Fig. 4. "Jumps" in transition boiling curves for different levels of heat transfer coefficients.

A horizontal line connecting the nucleate boiling curve and film boiling curve may be approached for a very large flow velocity and sub-cooling degree, as the dash line shown in Fig. 4. In this connection, the unstable transition boiling regime where the heat flux decreases with increasing wall superheat can be avoided or significantly reduced by increasing flow velocity and subcooled degree. In fact, relevant experimental observation can be found in the available literatures [11,12]. Peng et al. [11] experimentally found that the transition boiling regime would be reduced with increasing flow velocity and sub-cooling degree and tend to disappear at extremely high flow velocity and sub-cooling degree. Huang and Witte [12] found that the ratio of critical heat flux and minimum heat flux might approach to unity with a high flow velocity and sub-cooling degree. Regardless of the simplicity and completeness of the conceptual approach discussed herein, the present model could still provide a theoretical and quantitative foundation for the accurate control of transition boiling regime.

## 4. Conclusions

The present paper analyzed the temperature fluctuation correlation caused by lateral conduction in heater in transition boiling system and derived the critical correlation length, within which dry patches may interact to result in the occurrence of stable film boiling regime. The non-hydrodynamic transition to stable film boiling is then revealed. The present investigation not only provides comprehensive and rational insights on transition boiling mechanisms, but also may find industrial applications in controlling unstable transition boiling regime.

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