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# Heat transfer mechanisms in pool boiling

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## ABSTRACT

Pool boiling is a heat transfer mechanism carrying a phase transition from liquid to vapor. However, the exact characteristics of pool boiling are obscure because of the lack of the theoretical approach method. We have proposed a statistical thermodynamic heat transfer theory which is applicable to the heat transfer mechanisms of both conduction and internal convection. We here apply the heat transfer theory to pool boiling as an explicit illustration to understand the kinetics of phase transition mechanisms at the interface of two different phase materials. Three variable separation constants stand for particle number constants and play the key roles in exploiting the distinct boiling mechanisms. The theory accounts for the four boiling mechanisms of natural convection, nucleate boiling, transition boiling, and film boiling in pool boiling. It is able to match heat fluxes in wide ranges of temperature between wall temperature and saturation temperature in the four regimes. Three limiting heat fluxes and four activation temperatures are employed as input parameters. Theoretical heat flux-temperature curves agree with experimental heat flux profiles in a significantly broader range of temperature than those from any existing theories.

#### 1. Introduction

A phase transition is a vital subject in science and engineering since it is central to matter in the universe. Heat transfer is a driving force for a phase transition which is the transformation of a thermodynamic system from one phase of matter to another.

Pool boiling heat transfer has recently had various applications in reactors, rockets, distillation, air separation, refrigeration, and power cycles. Boiling is a phase transition process of heat transfer whose area is undergoing accelerating expansion. However, the complicated characteristics of pool boiling remain incompletely understood. In this context, a systematically unified theory for heat transfer in non-equilibrium, quasi-equilibrium, and equilibrium has been proposed [1].

We here apply the heat transfer theory [1] to pool boiling to prove the validity of the theory and to understand the detailed characteristics of pool boiling. The theory has a close analogy to the statistical thermodynamic theory for electrochemical reactions [2,3]. It can exactly account for heat flux profiles for the four mechanisms of natural convection, nucleate boiling, transition boiling, and film boiling. In other words, the heat transfer theory produces heat fluxes in pool boiling as a function of temperature, time, and space in the whole range of boiling regimes.

Since the pioneering investigation by Nukiyama's experiment [4], heat transfer in pool boiling has attracted great attention, from an empirical approach to theoretical understanding of boiling phenomena. The four mechanisms in pool boiling have been observed. Several physical mechanisms have been proposed for heat transfer occurring during the saturated boiling process [5]: microlayer evaporation [6], reflooding transient conduction [7,8], natural convection [9,10], microconvection [11-13], and combined mechanism models [14,15]. Nevertheless, the heat flux as a function of temperature has not been theoretically evaluated with complete satisfaction. The heat flux in a wide range of temperature has been only determined experimentally since theoretical correlations are valid only in the narrow regimes they were developed for. Existing theories such as the Rohsenow equation in nucleate boiling [11] reflect the heat fluxes in a narrow temperature regime of boiling. They do not predict both the limiting heat flux and the activation temperature of different boiling regimes. They cannot demonstrate the S-shape behavior of heat flux versus excess wall temperature.

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There is also a heat flux or temperature excursion at the initiation of nucleate boiling. The mismatch at the end of a natural convection regime and the inception of the nucleate boiling regime has been reported in Refs. [15–21] and an interpolation formula for the boiling curve has also been suggested by Bergles and Rohsenow [22]. Therefore, the reason for the mismatch deserves to be an important issue in understanding boiling, and a rigorous approach is required to clarify this phenomenon.

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#### Nomenclature

h	heat transfer coefficient	$t_{F}^{T}$	excess time from activation in transition boiling
k	spatial particle number	ť	excess time from activation in film boiling
$n_0$	particle number per unit volume	$Z^{c}$	excess distance from activation in natural convection
q	non-equilibrium heat flux vector	$Z^{N}$	excess distance from activation in nucleate boiling
q	heat flux	$Z'_{\Gamma}$	excess distance from activation in transition boiling
$q_1^0$	exchange heat flux	$Z^{r}$	excess distance from activation in film boiling
$q^1$	limiting heat flux		
$q^{e}_{c}$	external heat flux	Greek sy	vmbols
$q_{N}^{c}$	heat flux in natural convection	α	thermal particle number
$q_{T}^{N}$	heat flux in nucleate boiling	β	temporal particle number
$q'_{\Gamma}$	heat flux in transition boiling	λ	total mean free path
$q^r$	heat flux in film boiling	λο	mean free path
$T_0$	global equilibrium temperature	τ	total reaction time
$T_{p}^{0}$	local equilibrium temperature	$ au_0$	mean reaction time
Tp	excess temperature	$\sigma_c$	reaction cross section
t <sup>B</sup>	excess time	$\alpha_c$	thermal particle number in natural convection
$r^{D}$	excess displacement	$\alpha_n$	thermal particle number in nucleate boiling
n	unit vector	$\alpha_t$	thermal particle number in transition boiling
$T_w$	wall temperature	$\alpha_f$	thermal particle number in film boiling
$T_b$	activation temperature	$\beta_c$	temporal particle number in natural convection
t <sub>b</sub>	activation time	$\beta_n$	temporal particle number in nucleate boiling
$r_b$	activation distance	$\beta_t$	temporal particle number in transition boiling
$T_{nc}$	activation temperature in natural convection	$\beta_f$	temporal particle number in film boiling
$T_{nb}$	activation temperature in nucleate boiling		
$T_{tb}$	activation temperature in transition boiling	Subscrip	ts and superscripts
$T_{fb}$	activation temperature in film boiling	C Î	natural convection
$q_{1N}^{1C}$	limiting heat flux in natural convection	Ν	nucleate boiling
$q_{1T}^{1N}$	limiting heat flux in nucleate boiling	Т	transition boiling
$q_{1F}^{11}$	limiting heat flux in transition boiling	F	film boiling
<i>q</i> ''	limiting heat flux in film boiling	С	natural convection
$T^{c}$	excess temperature from activation in natural convec-	п	nucleate boiling
πN	tion	t	transition boiling
$T^{T}$	excess temperature from activation in nucleate boiling	f	film boiling
1' mF	excess temperature from activation in transition boiling	1	limiting value
I'	excess temperature from activation in film boiling	b	activation value
	excess time from activation in natural convection		
Ľ	excess time from activation in nucleate boiling		

### 2. Heat transfer theory for thermal non-equilibrium

A total system containing reactants and products is thermally isolated from its surroundings and is in thermal non-equilibrium while the two phases of reactants and products are in mechanical and chemical equilibrium. The system in thermal non-equilibrium is considered under the assumption that the physics of energy transfer can be described in terms of physical parameters in local thermodynamic equilibrium [23,24].

We propose a postulate that the heat flux can be described as a function of temperature, time, and space:

 $q = q(T, t, \mathbf{r})$ 

or, equivalently,

 $q = q(T, \partial T / \partial t, \nabla T),$ 

where T,  $\partial T/\partial t$ , and  $\nabla T$  are the generalized coordinates and velocities. It is anticipated that the three variables are independent and orthogonal. Furthermore, the expression of the heat flux can be written as a product of temperature, time, and space dependent terms:

 $q = q(T)B(t)A(\mathbf{r}).$ 

In this case, we can establish the Euler–Lagrange equation under the assumption of  $L \propto q$ :  $\nabla [\partial L/\partial (\nabla T)] + \partial/\partial t [\partial L/\partial (\partial T/\partial t)] - \partial L/\partial \phi = \mathbf{0}.$ 

Here, we may parameterize the variables during non-equilibrium processes like

 $\nabla T = T_0/\tau,$ 

 $\partial T/\partial t = T_0/\lambda.$ 

 $T_0$  is the equilibrium temperature.  $\tau$  is the total reaction time which is defined by the mean reaction time  $\tau_0$  multiplied by the particle number of the system, and  $\lambda$  is the total mean free path which is defined by the mean free path  $\lambda_0$  multiplied by the particle number of the system.

From the Euler–Lagrange equation leads to the partial differential equation for heat transfer [1]:

$$\lambda \nabla \cdot \boldsymbol{q} + \tau \,\partial q / \partial t - T_0 \,\partial q / \partial T = \boldsymbol{0},\tag{1}$$

where  $\mathbf{q} = q_T \mathbf{n} = q\mathbf{n}$  is the non-equilibrium heat flux vector with the unit vector  $\mathbf{n}$ . The first and the second terms on the left hand side of Eq. (1) originate from the kinetic energy densities and the third term comes from the thermal potential density. In the absence of the third term, Eq. (1) leads to the conservation of heat energy.

Using the method of separation of variables for the heat flux

$$q(T,t,\mathbf{r}) = q(T)B(t)A(\mathbf{r}),\tag{2}$$

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