



A thermodynamic analysis for heterogeneous boiling nucleation under an external electric field



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ABSTRACT

A generalized expression of chemical potential under external electric fields is derived based on the non-equilibrium thermodynamics theory. Using Gibbs free energy equilibrium condition, a thermodynamic model is developed for homogeneous and heterogeneous boiling nucleation under external fields. Taking into consideration the effects of electric fields strength, contact angle, and the temperature gradient in the superheated liquid layer, analytical solutions in integral forms for critical radius and availability are obtained for onset of heterogeneous boiling nucleation on a superheated wall. It is found that both the critical radius and availability increase with the enhancement of electric field strength, indicating that nucleation becomes more difficult to occur under an externally imposed electric field.

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1. Introduction

As an energy carrier, an electric field affects both the rate and the direction of phase change and the nucleation work by causing medium polarization, which has been widely discussed in the literature [1–5]. Although the classical nucleation theory was derived without an electric field [6], some experimental and theoretical studies on effects of electric field on nucleation on boiling and condensation process have been carried out recently [7]. In Kashchiev's book [7], it was stated that the critical radius of droplet is decreased and the critical nucleation work is reduced during the condensation process of supersaturated steam after imposing an electric field, which suggests that an electric field promotes the condensation of supersaturated steam. However, from many previous studies [2–5], it is uncertain whether an electric field would promote bubble nucleation in a superheated liquid. For example, some theoretical analyses [2,3] showed that an electric field inhibited boiling nucleation in a superheated liquid, while other experimental work [4,5] suggested that an electric field promoted boiling nucleation. Moreover, there were inconsistent conclusions on the effect of an electric field on the size of critical radius during bubble nucleation. For example, Saidi and Moradian [8] studied effects of uniform electric fields on homogeneous boiling nucleation from the view of thermodynamics. They took into consideration

effects of electric field on vapor/liquid interface energy by adding an electrical force in the Young–Laplace Equation. The results of their analysis showed that an electric field decreased the critical radius during bubble nucleation and facilitated bubble nucleation. On the other hand, Vorobev and Malysenko [9] calculated the minimum work required for homogeneous nucleation under an electric field based on grand thermodynamic potential, and found that the critical radius during boiling nucleation was increased while critical nucleation work was decreased after imposing an electric field, meaning that an electric field promoted bubble nucleation. The above mentioned researchers studied the effect of electric field on bubble nucleation with the phase equilibrium description from the view point of electric field effects on the change in availability or grand thermodynamic potential. Most recently, Quan et al. [10] carried out an experimental study on the effect of electric field on heterogeneous nucleation under pulse heating; they found that heat flux required for boiling inception is increased and the boiling nucleation time is delayed, implying that the electric field made bubble nucleation more difficult to occur.

In this paper, we will first deduce the generalized chemical potential under an electric field according to non-equilibrium thermodynamics [11] and the energy postulate [12], and then develop a mathematical model for critical radius and nucleation availability during both homogenous and heterogeneous nucleation based on the generalized chemical potential balance. It is shown that both the critical radius and the change in availability increase under an imposed electric field.

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Nomenclature

A area, m²
D electric displacement, C/m²
E electric strength, V/m
f quality force, J/kg
g specific Gibbs free energy, J/kg
G Gibbs free energy, J
h Enthalpy, J/kg
h_{fg} latent heat, J/kg
k temperature gradient of superheated liquid, K/m
m mass, kg
p pressure, Pa
r bubble radius, μm
R gas constant, J/(kg K)
s specific entropy, J/(K kg)
S entropy, J/K
T temperature, K
u specific internal energy, J/kg
U internal energy, J
v specific volume, m³/kg
V volume, m³
x distance in the fluid from the heated wall, m

ρ density, kg/m³
σ surface tension, N/m
Ψ availability, J

Subscripts

0 reference condition, initial state
b bubble
c critical state
G gas
i substance *i*
k substance *k*
l liquid
L liquid
n mass
q heat flow
s saturated state
sl solid and liquid
sv solid and vapor
T total mass
v vapor
w wall

Greek symbols

ε permittivity
ε₀ vacuum permittivity, F/m
μ chemical potential, J/kg
θ contact angle, deg

Superscript

Homo homogeneous nucleation

2. Homogeneous nucleation under an electric field

2.1. Changes in Gibbs free energy and critical radius

According to the non-equilibrium thermodynamics, an irreversible process will lead to entropy generation. The entropy generated during general irreversible process under an external field can be expressed as [11]:

$$\sigma = \sum_n J_n X_n = j_q \cdot \nabla \left(\frac{1}{T} \right) + \sum_k j_k \cdot \left[-\nabla \left(\frac{\mu_k}{T} \right) + \sum_i^{N-2} \frac{f_{ik}}{T} \right] - \frac{1}{T} \Pi : \nabla u + \sum_\rho \frac{A_\rho}{T} \varpi_\rho \tag{1}$$

where $f_{ik} = -\frac{\partial}{\partial n_k} \nabla(\zeta_{ik} \xi_{ik})$ is the mass force of the external field *i* on component *k* and other symbols in the above formula is listed in Table 1. Also, under an external field, the thermodynamic force driving the substance transmission of component *k* is:

$$X_k = -\nabla \left(\frac{\mu_k}{T} \right) + \frac{\sum_i^{N-2} f_{ik}}{T} = -\frac{1}{T} \nabla \left[\mu_k + \sum_i^{N-2} \left(\frac{\partial(\zeta_{ik} \xi_{ik})}{\partial n_k} \right)_{T,p,n_j} \right] = -\frac{1}{T} \nabla \mu'_k \tag{2}$$

where the generalized chemical potential under an external field is defined as [12]:

$$\mu'_k = \mu_k + \sum_i^{N-2} \left(\frac{\partial(\zeta_{ik} \xi_{ik})}{\partial n_k} \right)_{T,p,n_j} \tag{3}$$

For a single homogeneous substance with constant electric field strength and dielectric constant, the generalized chemical potential is reduced to:

$$\mu' = \mu + \frac{\partial(\zeta \xi)}{\partial n} \tau_{,p} \tag{4}$$

where ξ is the generalized extensive quantity of system electric field item, ζ is the conjugation of ξ , and $(\zeta \xi)$ denotes the energy of electric field, which is given by [13]:

$$\zeta \xi = \frac{1}{2} EDV \tag{5}$$

where the electric displacement $D = \epsilon E$, with ϵ being the absolute dielectric constant of substance, and E is electric field strength. Substituting Eq. (5) into Eq. (4) gives:

$$\mu' = \mu + \frac{\partial(\zeta \xi)}{\partial n} \tau_{,p} = \mu + \frac{\partial(\frac{1}{2} E \cdot DV)}{\partial n} \tau_{,p} = \mu + \frac{1}{2} E \cdot Dv = \mu + \frac{1}{2} \epsilon E^2 v \tag{6}$$

For the system consisting of a single substance, its specific Gibbs free energy is equal to the chemical potential, i.e.:

$$g' = g + \frac{1}{2} \epsilon E^2 v = h - Ts + \frac{1}{2} \epsilon E^2 v \tag{7}$$

Therefore,

Table 1
Thermodynamic flows and forces of irreversible process.

Irreversible process	<i>J_n</i>	<i>X_n</i>
Diffusion	Substance flow <i>j_k</i>	$-\nabla \left(\frac{\mu_k}{T} \right) + \sum_i^{N-2} \frac{f_{ik}}{T}$
Heat conduction	Heat flow <i>j_q</i>	$\nabla \left(\frac{1}{T} \right)$
Viscosity flow	Viscous stress tensor Π/T	$-\nabla u$
Chemical reaction	Chemical reaction ϖ_ρ	$\frac{A_\rho}{T}$

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