AVAILABILITY ANALYSIS FOR HETEROGENEOUS NUCLEATION IN A UNIFORM ELECTRIC FIELD

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Abstract Industrial demands for more compact heat exchangers are a motivation to find new technology features. Electrohydrodynamics (EHD) is introduced as a promising phenomenon for heat transfer enhancement mechanisms. Similar to any new technology, EHD has not been understood completely yet and requires more fundamental studies. In boiling phase change phenomena, nucleation is the dominant mechanism in heat transfer. Because of higher performance in heat transfer, nucleate boiling is considered as the main regime in thermal components. Hence, bubble dynamic investigation is a means to evaluate heat transfer. This study investigates bubble formation, including homogeneous and heterogeneous nucleation, from a thermodynamic point of view. Change in availability due to bubble embryo nucleation is discussed. Stability criteria for these systems are theoretically studied and results are discussed considering experimental data. In addition, a conceptual discussion on entropy generation in a thermodynamic system under electric field is presented.

Key Words Availability Analysis, Nucleation, Heterogeneous, Electric Field

چکیده تقاضای روزافزون صنعتی در زمینه فشرده سازی مبدلهای حرارتی عامل و محرکی در راستای رویکرد به فن آوریهای جدید می باشد. الکتروهیدرودینامیک بعنوان پدیده ای امید بخش به منظور افزایش انتقال حرارت با مکانیزمهای مختلف مورد توجه قرار گرفته است. در پدیده تغییر فاز جوششی، هسته زایی رژیم غالب است و به علت بالا بودن ضریب انتقال حرارت در این حالت از جوشش است که عموما در طراحی سیستمهای حرارتی مورد نظر می باشد. لذا بررسی دینامیک حباب معیاری برای ارزیابی انتقال حرارت خواهد بود. در این مقاله ایجاد حباب از نوع هسته زایی غیر همگن در حضور میدان الکتریکی و از دیدگاه ترمودینامیکی بررسی شده است. تغییرات در قابلیت کاردهی سیستم هنگام ایجاد و رشد نوزادهای حباب در چنین سیستمهایی بطور تئوری مطالعه شده و نتایج در کنار نتایج تجربی مورد بحث و بررسی قرار گرفته است. در انتها بحثی مفهومی پیرامون تولید انتروپی در چنین سیستمهای ترمودینامیکی که تحت تاثیر میدان الکتریکی قرار گرفته باشند ارائه شده است.

1. INTRODUCTION

Applying an electric field in heat transfer mechanisms is a very promising technique in the new generation of thermal and hydraulic equipments. Electro hydrodynamic phenomena, which are the result of electric and fluid flow field interactions, are not understood qualitatively yet, thus need more experimental and analytical study as a new interdisciplinary science. Interaction occurs in a dielectric fluid. The characteristics of electric field should be high voltage and low electrical current. The resultant electrical current in media is negligible. Resultant body forces affect hydro dynamically fluid flow and manifest its effect on each type of heat transfer regimes by individual scenarios. Surface destabilization and fluctuation of thermal resistant layer are the base motivations for transfer enhancement. Beside promising advantages such as lower power input, higher performance (in comparison to other active techniques), reduction in weight, volume and noise, and some other

important issues like pressure drop have been investigated further [1].

Bonjour et al. performed an experimental analysis of boiling under EHD effect and observed 400 to 1000 percent augmentations in heat transfer [2]. Markles et al. applied an AC electric field on water under atmospheric pressure, which is the earliest study on the bubble behavior under electric field [3]. Asch reported bubble size reduction and movement towards anode electrode [4]. Zhorzhorlani et al. used different fluids in boiling under electric field. [5]. Blachewicz reported bubble movement towards lower electric field intensity region [6]. Cooper studied pool boiling regimes and presented a simple theoretical model and also expressed Nusselt number increase as a result of hysteresis elimination and nucleation correction [7].

Kawahira et al**.** reported a decrease in the number and departure diameter of bubbles in experimented heat flux ranges[8]. Cooper [9] and Papar et al. [10] investigated electrode designs on EHD performance.

Ogata et al. reported 8.5 fold heat transfer enhancement and studied bubbles behavior. They expressed that normal component of electrostatic field (Maxwell stress tensor and electrostriction force) is responsible for compression of bubbles on heat transfer surface and radial component is responsible for horizontal movement of bubble on surface. They also observed an increase in the number of bubbles and their motion on transfer surface [11,12]. Salehi et al. studied pressure gradient imposed by electric field in the dielectric media [13]. Seyed-Yagoobi investigated pool boiling and compared two kinds of electrode design in a mixture of Freon - Oil and reported an increase in the rate of nucleation, not only because of lowering electrical relaxation time but also by lowering surface tension of fluid due to mixing [14]. Cho et al. investigated bubble behavior under DC electric field and expressed that the bubble is found to be extended in a direction parallel to the applied electric field. The elongation increases as the electric field strength increases. Consequently, the contact angle also increases with an increase in electric field strength if the contact radius is fixed. If the contact angle is fixed, the contact radius decreases as the electric field strength increases [15]. Di Marco et al. studied electric effects on pool boiling in a microgravity environment and reported that bubbles behavior (size and velocity) in a variable gravity altered drastically and concluded that EHD is a promising method to compensate lack of gravity in space applications [16]. Danti et al. studied experimentally effects of an external electric field on bubble dynamics. Detachment frequency and terminal velocity of bubbles were the main objective of their research. Reduction in departure diameter and increase in detachment frequency were reported [17]. Di Marco et al. experimentally investigated the influence of electric field on bubble growth in microgravity condition [18].

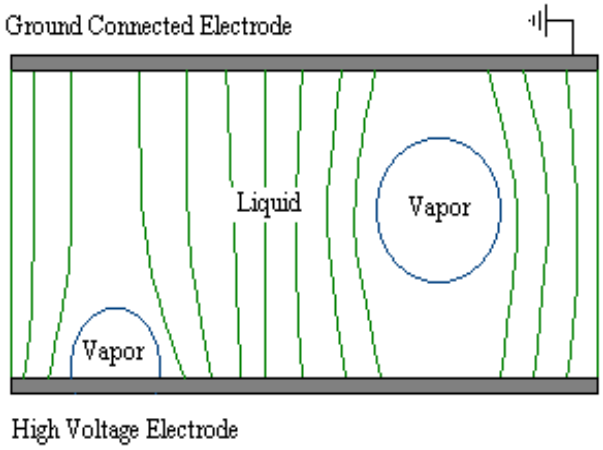
As stated before, most of the results on ebullition phenomena under EHD effect are experimental and due to lack of fundamental knowledge on EHD enhanced heat transfer [1], theoretical and fundamental points of view through these phenomena are highly required. Thus, in this study a fundamental thermodynamic point of view on bubble formation under the electric field effect, which has not been considered in the previous studies, is followed. Basic thermodynamic relations in a compressible system with an extra work mode (electrification or polarization work) are developed. Availability analysis through nucleation phenomena in heterogeneous systems (systems consist of two or more phases which are separated from each other by surfaces of phase boundaries [19]) are investigated and discussed. Homogeneous and heterogeneous nucleation is considered individually. A separate study on stability criteria for homogeneous single component compressible systems under EHD effect is developed as well. Finally, some overall expressions on entropy generation (or exergy destruction [20]) are represented.

2. BUBBLE BEHAVIOR UNDER EHD PHENOMENA

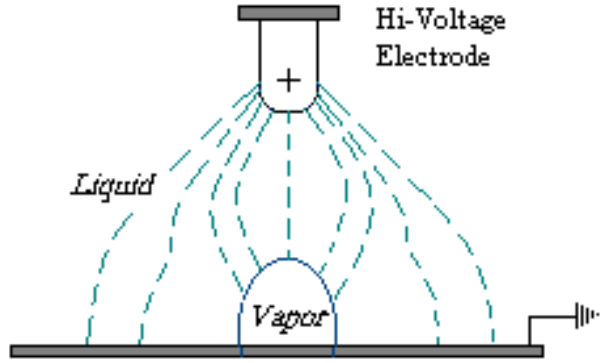
EHD enhancement method arises from electric body force density acting on molecules of a dielectric fluid in the presence of an electric field, which consists of three terms [1]:

$$f_b = \rho_e E - \frac{1}{2} E^2 \nabla \varepsilon + \frac{1}{2} \nabla \left[E^2 \left(\frac{\partial \varepsilon}{\partial \rho} \right)_T \rho \right] \qquad (1)$$

The first term refers to the action of the electric field on free charges and represents the Coulomb



(a) Uniform electric field



(b) Nonuniform electric field

Figure 1. Simple schematic of a uniform electric field interaction on a spherical bubble.

force (or electrophoresis). The second and third terms represent the dielectrophoresis and electrostriction force density, which are referred to as polarization forces induced in the fluid. To clarify the effect of an electric field on pool boiling, different mechanisms of electrically induced liquid-vapor motion should be explained.

A charged body in a uniform or nonuniform electric field will move along electric field lines. Dielectrophoresis force is the result of polarization force in a nonuniform electric field. Polarization is generated by relative displacement of positive and negative charges of a neutral body, which occurs because of one main reason, the fluid nonhomogenity, which is caused by position or density variation. When a bubble is in an electric field, the force exerted by the second term in Equation 1 is the dominant force and forces the bubble (lower permittivity) to the region of lower electric field intensity. In Figure 1 a schematic representation of an electric field interaction on bubble is shown.

In cases when there is no bulk free charge in the surrounding liquid, the electric potential around the bubble satisfies the Laplace equation:

$$\nabla^2 \phi = 0 \qquad (2)$$

In addition, proper boundary condition corresponding to geometry should be considered.

Cho at. al. [15] and Ogata et al. [12] investigated the following conditions:

$$\phi = -E_\infty r \cos\theta \quad \text{when} \quad r \to \infty$$

$$n \cdot \nabla\phi = 0 \quad \text{on bubble surface} \qquad (3)$$

$$\phi = 0 \quad \text{at} \quad \theta = \tfrac{\pi}{2}, y = 0$$

Figure 2 shows a schematic of equipotential lines around an attached bubble during growth [11,15]. When an electric field is used, the bubble departure diameter decreases. The electric field forces bubbles

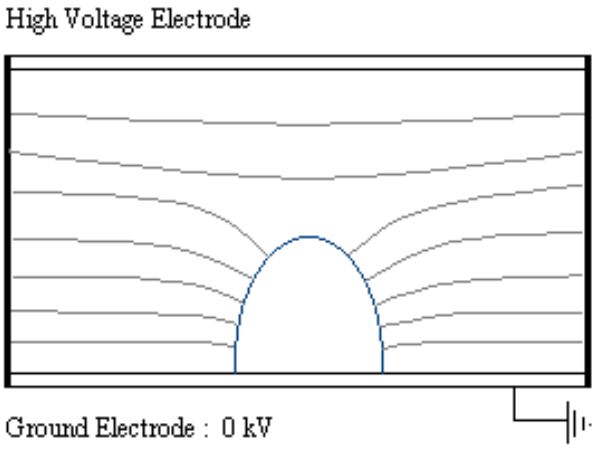


Figure2. Equipotential lines around an attached bubble in a uniform electric field.

near the heat transfer surfaces and improve mixing and turbulence, which leads to heat transfer enhancement [7,8]. In most cases, a large reduction in wall superheat for the onset of nucleation is observed. This phenomenon is explained by alteration of nucleation sites during EHD compared to normal nucleation sites, which take place in normal boiling (in the absence of electric field). Taylor instability of the bubbles in EHD phenomena results in smaller bubbles [11,12].

The relaxation time of the electric field (the time taken for the electric force to begin affecting the generated bubbles) is also a significant factor. Heat transfer enhancement in nucleate boiling is mainly due to two mechanisms namely electroconvection and effects on dynamics of bubbles; both depend on electric field intensity and relaxation time. When relaxation time is much higher than bubble frequency, bubbles are unaffected by the electric field and electroconvection is the main mechanism for heat transfer augmentation.

Experimental results show that the electric field does not adversely affect the refrigerant-oil mixture. This can be counted as an advantage of EHD phenomenon to enhance heat transfer.

As reported, the heat transfer coefficient of the rough surface is higher than that of the original surface without an electric field. However, in most cases, when the voltage is applied, the difference becomes smaller. This means that the major mechanism of heat transfer has changed from nucleate boiling to forced convection of the thermal boundary layer near the solid phase [8].

An increasing number of bubbles is the general result of electric field imposition [12,21], however in lower heat fluxes mode of boiling may changes so that natural convection improvement leads to lower heat fluxes to be exchanged by bubble formation (phase change or latent heat), hence nucleation weakens. On The other hand, bubble density may reduce.

3. CHANGES IN AVAILABILITY FUNCTION DURING NUCLEATION PHENOMENON

For a liquid heated at a constant pressure above its equilibrium boiling temperature the spinodal limit (locus for sign alteration of $\left(\frac{\partial p}{\partial v}\right)_T$ which can be achieved by connecting the extermum points of constant temperature curves obtained by the Van der Waals equation of state on a P-V diagram) is the maximum upper limit on the superheat resulting from thermodynamic considerations. For states near the liquid saturation line, density fluctuation in the liquid may results in a localized region where the molecular density has been lowered to almost that of saturated vapor extreme. Fluctuations of this type may lead to small embryo bubbles (Heterophase Fluctuations) [22].

We denote the availability by ψ which usually expresses the maximum work, and can be exchanged between a system and the environment when dead state is achieved.

For equilibrium condition, changes in availability should be zero and in order to have stable equilibrium it should be minimized. Spontaneous internal changes always decrease the availability of any system [19].

Consider a system of liquid in two states. In the first, only the liquid phase has filled the system and finally, a bubble embryo is generated. p_l and T_l are assumed to be liquid phase pressure and temperature respectively, and also the reference state. r, p_v and T_v represent the radius of the bubble, and pressure and temperature of vapor inside the bubble. Liquid pressure is lower than the saturation pressure in T_l. Initially, all of the liquid is in metastable state (superheated) and the corresponding availability is indicated by ψ_0.

After creation of the bubble embryo, availability is defined in such a way as to include three parts [23,24]:

$$\psi = \psi_l + \psi_v + \psi_i \qquad (4)$$

where ψ_v, ψ_l and ψ_i are availability caused by vapor in the bubble, liquid around the bubble and free energy on the interface, respectively.

It should be noted that ψ_i is the contribution due to interfacial tension, which is equal to the work done to create the interface.

Up to this point, we have considered each phase as a single component system with only one work mode that was due to compression. To investigate the electric field effect, fundamental thermodynamic relations are developed for such a system with an

extra work mode, which is the result of electric field imposition. Electric field can result in a work mode presented by [19,25,26]:

$$\delta W = \int E \cdot \delta D d\overline{V} \tag{5}$$

where W, E, D and $\overline{V}$ denote electrical work, electric field strength, electric displacement and volume of dielectric in the electric field.
By considering electrical mode in addition to compression, we would find a thermodynamic relation responsible for internal energy changes as:

$$dU = TdS - PdV + \sum_{1}^{k} \mu_i dn_i + E \cdot dD \tag{6}$$

By using Euler theorem on homogeneous functions we get:

$$G = U - TS + PV - E \cdot D \tag{7}$$

It is assumed that U is yet a homogeneous function with respect to properties.

By eliminating terms indicating heat flux to environment between the first and the second laws of thermodynamics in addition to assumption of independence of dielectric constant from temperature (in an analogy to usual thermodynamics [20]). The appropriate definition for non-flow availability (exergy) would be developed as:

$$\psi = U - T_0 S + P_0 V - E_0 D \tag{8}$$

The subscript " 0 " indicates reference state. Thus, reversible work mode would be represented by changes in availability function. It should be noticed that in most engineering situations, a linear relation between displacement and electric field strength is used.

$$D = \varepsilon E \tag{9}$$

The vapor inside the bubble is at a temperature T_l which is equal to that of the surrounding liquid but the pressure must be different and satisfy the Young-Laplace equation. In order to simplify, it is assumed that the electric field does not seriously deviate due to bubble presence. Thus appropriate functions contributed to vapor-liquid and interface are:

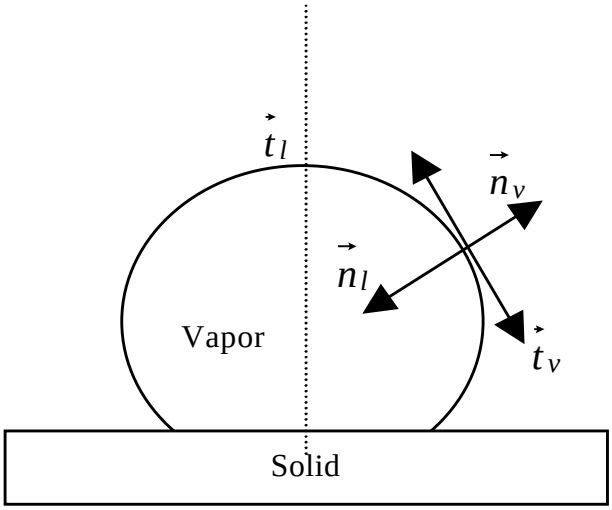


Figure 3. Electric stresses acting on an interface.

$$\psi_l = (m_t - m_v)(u_l - T_l s_l + p_l v_l) = (m_t - m_v) g_l(T_l, p_l) \tag{10}$$

$$\psi_v = m_v(u_v - T_l s_v + p_l v_v) = m_v[g_v(T_l, p_l) + (p_l - p_v)v_v] \tag{11}$$

$$\psi_i = (A_{sl}\sigma_{sl})_f + A_{sv}\sigma_{sv} + A_{lv}\sigma_{lv} + \tau_{m.s.} \cdot V \tag{12}$$

σ represents surface tension.
Also;

$$\psi_0 = m_t g_l(T_l, p_l) + (A_{sl})_i \sigma_{sl} + \left(\frac{\varepsilon_0 E^2}{2}\right)\left(\Delta\varepsilon + \frac{(\varepsilon_l - 1)(\varepsilon_l + 2)}{3}\right) \cdot V_l \tag{13}$$

$\tau_{m.s.}$ is the Maxwell stress tensor. It is assumed that a uniform electric field is applied on the system before and after the bubble embryo is formed

The Maxwell stress tensor in indicial form is represented by [1,26]:

$$\tau_{ij} = \varepsilon E_i E_j - \frac{\varepsilon}{2} \delta_{ij} E_k E_k \left[1 - \frac{\rho}{\varepsilon} \left(\frac{\partial \varepsilon}{\partial \rho} \right)_T \right] \quad (14)$$

The liquid–vapor interface (Figure 3) is affected by the resultant of two stresses:

$$f_s = f_{sn} + f_{st} \quad (15)$$

By considering electric field continuity on interface:

$$\varepsilon_l E_{ln} = \varepsilon_v E_{vn} \quad (16)$$

$$E_{lt} = E_{vt} \quad (17)$$

and using Equation 1, EHD force components on interface is obtained as:

$$f_{sn} = \frac{1}{2} \left[\varepsilon_l \left(E_{ln}^2 - E_{lt}^2 \right) - \varepsilon_v \left(E_{vn}^2 - E_{vt}^2 \right) \right. \\ \left. \rho_l \frac{d\varepsilon_l}{d\rho_l} E_l^2 - \rho_v \frac{d\varepsilon_v}{d\rho_v} E_v^2 \right] \vec{n}_l \quad (18)$$

$$f_{st} = \left(\varepsilon_l E_{lt} - \varepsilon_v E_{vt} \right) \vec{t}_l = \left(\varepsilon_l E_{ln} - \varepsilon_v E_{vn} \right) E_{vt} \vec{t}_l \quad (19)$$

$\vec{n}_l$ is the unit normal vector towards liquid phase and $\vec{t}_l$ is the tangential vector to the interface.

In order to linearize the nonlinear terms in the stress relation, the Clausius-Mossoti relation is used [13,25]:

$$\frac{\rho}{\varepsilon} \frac{\partial \varepsilon}{\partial \rho} = \frac{(\varepsilon_l - 1)(\varepsilon_l + 1)}{3} \quad (20)$$

The dielectrophoresis (caused by the permittivity gradient) is responsible for induced motion of the bubble (or deformation). Thus, Maxwell stress is considered in interfacial availability function. Then ψ_i would be rewritten as:

$$\psi_i = 4\pi r^2 \left[\sigma + \frac{1}{3} \left(\frac{\varepsilon_0 E_l^2}{2} \right) \left(\Delta\varepsilon + \frac{(\varepsilon_l - 1)(\varepsilon_l + 2)}{3} \right) \right] \quad (21)$$

ε_0 and $\Delta\varepsilon$ represent vacuum permittivity and difference between liquid and vapor dielectric constants, respectively. In the equilibrium state of the bubble, the Young-Laplace equation is modified to [11]:

$$p_v - p_l = \frac{2\sigma}{r} - \left(\frac{\varepsilon_0 E^2}{2} \right) \left(\Delta\varepsilon + \frac{(\varepsilon_l - 1)(\varepsilon_l + 2)}{3} \right) \quad (22)$$

Initial availability of the system is defined as:

$$\psi_0 = (m_l + m_v) g_l (T_l, P_l, E_l) \quad (23)$$

The final availability function can be represented by Equation 4 and denoted by ψ_{tot}.

As stated before, electric field inside the embryo is almost the same as surrounding. D and E are assumed linearly dependent and electric field does not change physical properties of medium seriously. Because of relatively small volume of bubble embryo these assumptions are logical and have been used in some literatures [11,12,15].

In chemical equilibrium condition for the multicomponent two-phase systems, chemical potential (or in most cases Gibbs function) of all the phases of each component are equal in equilibrium state.

By setting:

$$B = \frac{\varepsilon_0 E^2}{2} \left(\Delta\varepsilon + \frac{(\varepsilon_l - 1)(\varepsilon_l + 2)}{3} \right) \quad (24)$$

Bubbles smaller than the critical radius tend to collapse and larger bubbles tend to continue to grow spontaneously.

In order to investigate the changes in availability or stability criteria of vapor embryos within bulk liquid during thermodynamic nonequilibrium, while bubble is close to mechanical equilibrium, the $\Delta\psi$ relation should be rearranged. The phrase close to mechanical equilibrium represents that equality in the Young-Laplace equation fails and changes to approximate equality [22,24].

For this purpose we use n and μ to denote the number of vapor molecules in the bubble and the chemical potential, respectively.

Chemical potential changes for the present system

TABLE 1. Electrical Property Data of R-134a to Determine Changes in Availability Function.

T_{sat}	ε_l	ε_v
$^\circ C$	pF/m	pF/m
5	104.6	10.6
25	90.0	11.5

is developed as :

$$d\mu = Vdp - SdT - DdE \quad (25)$$

Assuming an Ideal gas for vapor inside bubble, infinitesimal changes in electric field due to embryo presence and spherical shape for bubble embryo during growth.

In order to demonstrate the results, R-134a is selected as working fluid with electrical properties listed in table 1 [1].

Electric field strength is 20-kV. Pressure of the system is assumed one atm and saturation temperature as $20^\circ C$; hence, saturation pressure corresponding to this temperature is 0.571 MPa. Vapor pressure inside the bubble is calculated as 0.570 MPa, thus the required thermodynamic condition for homogeneous nucleation in superheated liquid is achieved.

4. CHANGES IN AVAILABILITY THROUGH HETEROGENEOUS NUCLEATION

Formation of a vapor embryo at the interface between a metastable liquid and another solid phase is one type of heterogeneous nucleation. With a liquid phase at a uniform temperature T_l and pressure P_l, the vapor embryo will be at temperature T_l but at a pressure P_v.

For an attached bubble embryo assuming that the embryo shape is nearly spherical with radius r, Figure 4 shows attached bubble embryo schematically.

Bubble volume and common surfaces between three interacting phases are [22,24]:

$$V_v = \frac{\pi r^3}{3}\left(2 + 3\cos\theta - \cos^3\theta\right) \quad (26)$$

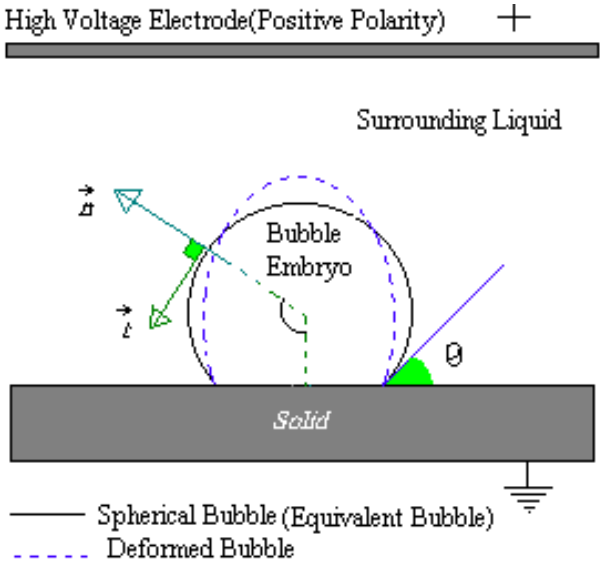


Figure 4. Attached bubble embryo on solid surface as a heterogeneous nucleation.

$$A_{lv} = 2\pi r^2(1 + \cos\theta) \quad (27)$$

$$A_{sv} = 2\pi r^2(1 - \cos\theta) \quad (28)$$

here θ, A_{lv} and A_{sv} are the contact angle, interface area between liquid-vapor and interface area between solid-vapor respectively. $(A_{sl})_i$ and $(A_{sl})_f$ represent initial and final area between solid and liquid phase. Thus:

$$(A_{sl})_i - (A_{sl})_f = A_{sv} \quad (29)$$

$$\sigma_{sv} - \sigma_{sl} = \sigma_{lv}\cos\theta \quad (30)$$

where σ_{sv}, σ_{sl} and σ_{lv} indicate surface tension coefficients between solid-vapor, solid-liquid and liquid–vapor respectively. By a similar procedure as followed in homogeneous nucleation we would obtain:

$$\Delta\psi = m_v(g_v - g_l) + (P_l - P_v)V_v + A_{sv}(\sigma_{sv} - \sigma_{sl}) + A_{lv}\sigma_{lv} + BV_v \quad (31)$$

$$\Delta\psi_e = \left(B - \frac{2\sigma}{r_e}\right)V_v + A_{sv}\sigma_{lv}\cos\theta + A_{lv}\sigma_{lv} + BV_v$$
$$= \left(\frac{\pi r_e^3}{3}\right)\left(2 + 3\cos\theta - \cos^3\theta\right)\left[2B - \frac{2\sigma}{r_e}\right] +$$
$$2\pi r_e^2\sigma_{lv}\left(2\cos\theta - \cos^3\theta + 1\right) \quad (32)$$

For nonequilibrium state, a similar procedure similar to that of the homogeneous nucleation is followed and finally becomes:

$$\Delta\psi = \Delta\psi_e + x\left(\mu_v - \mu_l\right) \quad (33)$$

Hence:

$$\Delta\psi = \Delta\psi_e + \left(P_l + \frac{2\sigma}{r} - B\right)V_v\left[\ln\frac{P_l + \frac{2\sigma}{r} - B}{P_l + \frac{2\sigma}{r_e} - B}\right] \quad (34)$$

5. RESULTS AND DISCUSSIONS

Figure 5 shows that there is always a maximum contact angle, which behaves in a linear manner with respect to electric field intensity.

Figure 6 shows that existence of a maximum in availability change towards equilibrium is affected linearly with surface tension coefficient and indicates that for liquids with higher surface tension, the maximum contact angle in a fixed electric field is increased.

Figure 7 shows that at a fixed contact angle, increasing radius results an increase in $\Delta\psi$. This can be expressed as a result of volume increase of bubble embryo. By assumption of a fixed attached radius, increase in contact angle reduces availability function. In order to explain this behavior, Maxwell stress effects on embryo should be considered. At higher contact angles, the electric field can compensate availability reduction.

In Figure 8 two curves are shown, namely the curve with 20 kV applied electric field and the curve without electric field implementation. While electric field is eliminated from the system, as expected before, a peak in the availability curve occurs which is in coordination with the second law of thermodynamics (this agreement has been described before). By imposing electric field as an external work on the system, rise in availability is achieved.

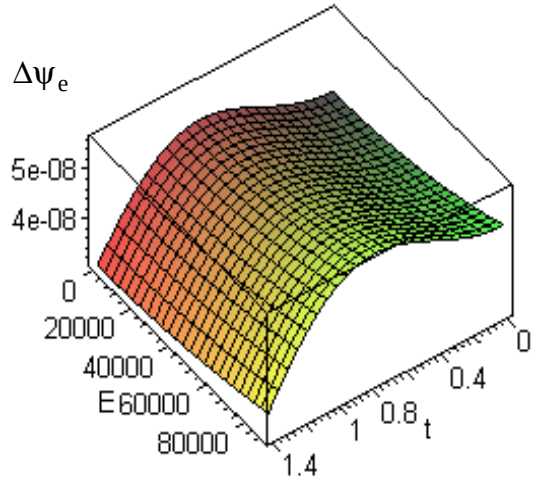


Figure 5. Change in availability of the system in equilibrium state with respect to contact angle and electric field intensity.

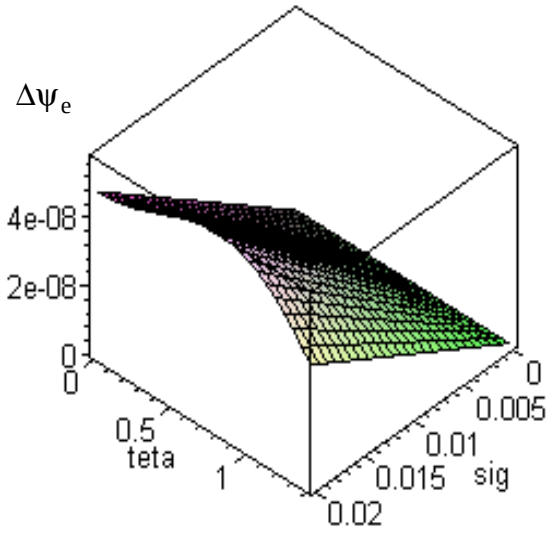


Figure 6. Change in availability of the system in equilibrium state with respect to contact angle and surface tension.

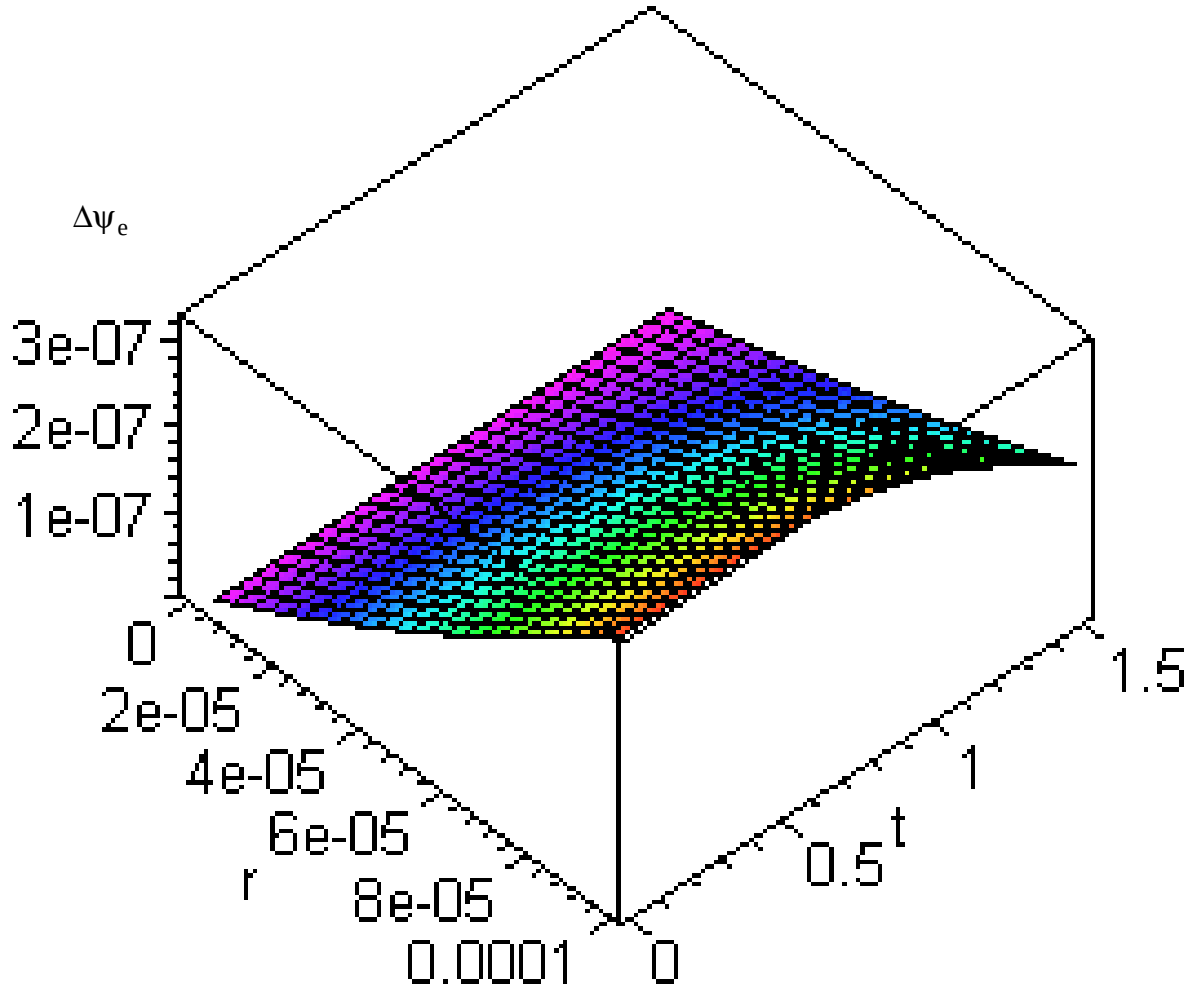


Figure 7. Change in availability with respect to initial state versus radius and contact angle.

6. GENERAL DISCUSSION

Entropy Generation Heat transfer across a finite temperature gap always contributes to destruction of available work or in the other hand, entropy generation. Simple entropy production for such a system is:

$$S_{gen} = \frac{\dot{Q}}{T_{low} T_{hot}} \Delta T \succ 0 \quad (35)$$

As Equation 35 shows, isolating, which results in lowering heat flux dissipation, or decreasing temperature difference between objects, can decrease entropy generation [20]. Thus, as reported in experimental results on electro hydrodynamic systems [11], a large decrease in required superheat is observed. Without considering other effects, it can be inferred that this technique would lead to lowering destruction of availability (exergy).

By considering the work of the electric field and drag force on a moving bubble with almost constant volume, the first and second laws of thermodynamics can be written as:

$$dU = TdS - PdV + EdD \quad (36)$$

$$S_{gen} = \frac{dS}{dt} \quad (37)$$

Hence, by combining Equations 36 and 37 also

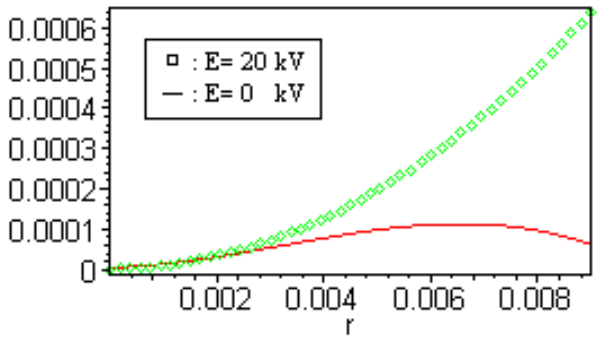


Figure 8. Change in availability with and without an electric field imposition versus radius.

using an expression for electric field work on a dielectric liquid media [19,25,26] we get:

$$F_d U_\infty - \int E \cdot \delta D d\overline{V} = U \qquad (38)$$

where U_∞, F_d, $\overline{V}$ and U are the bulk fluid velocity, drag force, bubble volume and internal energy, respectively. It should be noted that this discussion is in such a condition that the electric field pushes the bubble to get away from heat transfer surface. (like most experiments in this field [15,17]). Thus, the generated entropy may be written as:

$$S_{gen} = \frac{d}{dt}\left(F_d U_\infty - \int E \cdot \delta D d\overline{V}\right) \succ 0 \qquad (39)$$

Equation 39 indicates that despite an increase in entropy generation increment caused by drag force on a moving bubble, the electric field would manifest an opposite effect.

7. CONCLUSIONS

To realize the effect of EHD enhancement on availability criteria of heterogeneous nucleation, a theoretical investigation has been performed.

Results are in precise agreement with the expected thermodynamic predictions and accessible experimental reports.

Variations in Bubble radius and contact angle, which are the most significant parameters in heterogeneous nucleation, were taken into account with and without EHD enhancement.

EHD is confirmed to be a promising method to enhance boiling heat transfer regime.

It was demonstrated that the capabilities of EHD technique considering entropy generation in view of the second law of thermodynamics, leads to desirable approach.

8. NOMENCLATURE

A_{lv}	liquid-vapor area (m^2)
A_{sl}	solid-liquid area (m^2)
A_{sv}	solid-vapor area (m^2)
C_v	specific heat (J/kg K)
B	defined by Eq. (24)
D	electrical displacement (pFV/m^2)
E	electric field strength (V/m)
E_i	electric field strength in x direction
E_j	electric field strength in y direction
f_b	EHD force density (N/m^3)
F_d	drag force (N)
g_l	Gibbs function for liquid phase (J/kg)
g_v	Gibbs function for vapor phase (J/kg)
G	Gibbs function (J)
m_l	liquid mass (kg)
m_v	vapor mass (k)
n_i	number of vapor molecules
n	number of gas moles
p	pressure (Pa)
p_l	liquid pressure (Pa)
p_v	vapor pressure (Pa)
R	universal gas constant (J/kmoleK)
r	bubble embryo radius (m)
r_e	equilibrium radius (m)
S	entropy (J/K)
S_{gen}	entropy generation (J/sec K)
T	temperature (K)
T_l	liquid temperature (K)
T_{sat}	saturation temperature (K)
T_{low}	cold source temperature (K)
T_{hot}	hot source temperature (K)
U	internal energy (J)

U_∞	bulk fluid velocity (m /s)
u_l	liquid internal energy (J)
u_v	vapor internal energy (J)
V	volume (m^3)
v_l	specific volume of liquid (m^3/kg)
v_v	specific volume of vapor (m^3/kg)
$\overline{V}$	total volume of dielectric (m^3)
W	electric filed work (J)
x	vapor quality

Greek Symbols

ρ	density (kg/m^3)
δ_{ij}	kronecker delta
θ	contact angle (Rad)
σ	surface tension (N/m)
ε	dielectric permittivity (pF/m)
ε_0	vacuum permittivity (pF/m)
ε_l	liquid permittivity (pF/m)
ε_v	vapor permittivity (pF/m)
μ_l	liquid chemical potential (J)
μ_v	vapor chemical potential (J)
μ_i	chemical potential of ith component (J)
$\tau_{m.s.}$	Maxwell stress tensor (N/m^2)
τ_{ij}	Maxwell stress tensor components (N/m^2)
ψ	availability function (J)
$\Delta\psi$	change in availability with respect to initial state (N/m^2)
$\Delta\psi_e$	change in availability, equilibrium state with respect to equilibrium state (N/m^2)

Subscripts

e	equilibrium
I	initial state
f	final state
v	vapor
l	liquid
tot	total
sat	saturation
sl	solid-liquid
gen	generation
lv	liquid-vapor
sv	solid-vapor

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