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A Review on the Studies of Heat Transfer Enhancement within Electric Fields

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Abstract: Some studies of electro-hydrodynamic (EHD) heat transfer enhancement methods were reviewed and some results mentioned. EHD methods was divided into phase change and single phase heat transfer processes. In the former, the effect of EHD on boiling, evaporation and condensation was studied and in the later, some researches about natural convection in the presence of electric field and corona wind was reviewed. Researches in this field are continued and the expected area of application is in the thermal control systems in space stations.

Keywords: Enhancement, Electro-hydrodynamic, Heat Transfer, Phase Change, Single Phase.

مروری بر مطالعات انجام شده در مورد افزایش انتقال حرارت در میدان‌های الکتریکی

یاسر شفیعی الموتی– عضو گروه تبدیل انرژی، دانشکده مهندسی مکانیک، دانشگاه آزاد اسلامی واحد تاکستان

چکیده: در این مقاله برخی مطالعات انجام شده در مورد روش‌های افزایش انتقال حرارت در پدیده الکترو- هیدرودینامیک بررسی و برخی موارد استنتاج می‌شوند. فرآیندهای انتقال حرارت در روش‌های الکترو- هیدرودینامیک به دو دسته تکفازی و تغییرفاز تقسیم می‌شوند. در گروه اخیر، اثر الکترو- هیدرودینامیک در جوش، تبخیر و میعان مطالعه شده ئ در دسته اول، برخی محققان اثر جابجائی را در میدان الکتریکی و باد کرونا مرور نموده‌اند. تحقیقات در این زمینه ادامه داشته و انتظار می‌رود کاربردهای خاصی در کنترل حرارتی سامانه‌های فضائی پیدا نماید.

واژه‌های کلیدی: تقویت انتقال حرارت، الکترو- هیدرودینامیک، تکفازی و تغییرفاز.

1. Introduction

Energy and material saving considerations, as well as economic incentives, have led to expansion of efforts to produce more efficient heat exchange equipments. Common thermal-hydraulic goals are to reduce the size of a heat exchanger required for a specified heat duty, to upgrade the capacity of an existing heat exchanger required, to reduce the approach temperature difference for the process streams, or to reduce the pumping power. The air conditioning and refrigeration industry need equipments with increased efficiency. Study of improved heat transfer performance is referred to as heat transfer augmentation, enhancement or intensification. In general, this means an increase in the amount of heat transfer with a finite temperature difference. The method can either enhance heat transfer area or increase Heat transfer coefficient. For example, one of the biggest contributors to these increased heat transfer, in the past, has been the use of attached or integral fins that extend the heat transfer area. Another one is rough surfaces that intensify the turbulence and increase the heat transfer coefficient. Today, a radically new method of increasing heat transfer coefficient called electro–hydrodynamic (EHD) technique is being investigated, uses the electric fields. The heat transfer enhancement with electric field is considered as a result of the reduced thermal resistance, secondary flow induced by electric field and/or the promotion of the turbulence ([1]). Heat transfer enhancement mechanism, in this method, differs in different apparatuses depending on the equipments and certain condition. In this paper, the EHD forces act on the fluids was mentioned and several different ways of using EHD in heat transfer heat was reviewed

2. EHD Forces Acting on a Continuum Media

EHD phenomena involve the interaction of electric fields in a dielectric fluid medium. This interaction can result in electrically induced fluid motion and interfacial instabilities which are caused by an electric body force. The magnitude of this force density acting on the molecules of a dielectric fluid in the presence of an electric field can be calculated by considering energy and electric charge conservation and consist of three terms that for electrically linear media with polarization dependent on mass density is as follows ([2]):

$$\vec{F} = \rho_f \vec{E} - \frac{1}{2} E^2 \nabla \varepsilon + \nabla \left(\frac{1}{2} \rho \frac{\partial \varepsilon}{\partial \rho} E^2 \right) \quad (1)$$

The three terms in Eq. (1) stand for two primary force densities acting on the fluid. The first term represents the Coulomb force acting on the free charges in the presence of an electric field and is known as electrophoresis force ([3]). Free charges can be established in the fluid medium by direct injection of free charges or by means of a corona discharge. The second and third terms represent the polarization forces induced in the fluid. Second term is due to in–homogeneities and local change of the electric permittivity. A change in permittivity occurs, for example, at the interface of a vapor bubble with a liquid. This term is called die–electrophoresis force ([4]). Finally, the third term stands for electrostriction force occurs primarily when a non–uniform electric field is applied on a dielectric fluid. All three components of EHD force densities can be significant or one can dominate over the others.

3. Influence of EHD Forces on Heat Transfer

EHD Effects on heat transfer generally differ from case to case and depend on several conditions such as heat transfer fluids or geometry of devices. Also, whether or not the process is phase change greatly affect the mechanism of influence of EHD forces. So here, study of the effects is divided into phase change and single phase processes.

3.1. Phase Change Processes

Existence of the liquid-vapor interface in phase change processes lead to a great die–

electrophoresis force. Some researches about Boiling, evaporation and condensation will be reviewed in this section.

Boiling: Many researches were done in this field either in pool boiling or in convective boiling. By applying an electric field to a boiling dielectric fluid in pool boiling, both the vapor bubble dynamics and the liquid motion are modified. It has been reported that the aspects of boiling changes when an electric field is applied ([5]). While EHD enhancement of boiling heat transfer has been extensively studied, the fundamental effects of EHD on bubble dynamics, and hence the boiling process has not been completely quantified. In the tests, a hot one wire or a tube is used as a heat transfer surface and electrodes are longitudinal wires, parallel to the surface, or annular wires. One of the first researches was done by Bonjour *et al.* [6] that reported the suppression of boiling of various organic fluids such as hydrocarbons under a high electric field. With longitudinal electrodes and applied voltages between 0-25 kV, for the test liquid of a mixture of R-11 and ethanol which is initially 2 wt %, various boiling phenomenon are observed ([7]). When the applied voltage exceed 10 kV, boiling was suppressed and the number of boiling bubbles decreases which is the same phenomena that occurs with pure R-11 ([8]). However with a voltage of about 15 kV, boiling abruptly became active and the number of bubbles increased. Finally, the enhancement ratio of about 8.5 times the maximum of that with no electric field was reported for a mixture of dielectric fluid, R-11, and conductive fluid, ethanol that is very greater than that for pure R-11. The reason for the greater heat transfer augmentation in the mixture is considered as follows: there are two effects of high electric fields, one is the electro-convection and another is the effect on behavior of bubbles. Both effects are dependent on the electric field strength and the relaxation time of the electric charge. For pure R-11 the electric charge relaxation time is 1.3 s while the characteristic time of boiling fluid that is the generation frequency of boiling bubbles of R-11 is about 0.02 s. this means that the charge relaxation time is far greater than the bubble frequency and the generated bubbles are not affected by the electric field. Only the electro-strictive effect on the thermal boundary layer, due to the in-homogenous electric field around the wire electrodes, contributes to the enhancement of heat transfer. On the other hand, this convective effect is the cause of boiling suppression by decreasing the wall superheat ([8]). Now when ethanol which is conductive is added to dielectric fluid, R-11, (only several percent of the total weight), the relaxation time decreases, become much smaller than the bubble frequency. As a result, bubbles are pressed against the heat transfer surface due to the alternating electric potential distribution corresponding to the bubble motion. These phenomena are considered to be effective for the augmentation of heat transfer ([7]). Another reason could be the decrease in surface tension of dielectric because of the presence of ethanol. This results in a homogenous nucleation with smaller critical radius of vapor embryo and consequently the greater amount of heat transfer in the form of latent heat ([4]). Wire electrodes produce inhomogeneous electric field. For the homogenous electric field lattice type rectangular electrodes can be used. In this case, enhancement of natural convection and suppression of latent heat, for pure R-123, is reported ([3]). With the model of *Paul and Abdel-Khalik* [5], the total heat flux in nucleate boiling is divided into three parts: Latent heat transfer, forced convection and natural convection. In fact, in addition to the latent heat, convection from that portion of the heated surface not occupied by bubbles accounts for the remainder of the heat flux. This convection is divided into two components: natural convection and forced convection. Forced convection arisen by the agitation of the thermal boundary layer by the bubble growth and departure on the heated surface. The relative contributions of this three mechanisms as the total heat flux is increased from boiling incipience to burnout can be quantified from measured values of the number of active nucleation sites, bubble departure diameter and bubble departure frequencies. As in the previous case, for a given heat flux, application of the electric field, enhances natural convection, as shown in Fig. (1), thereby suppressing boiling because of the lower heated surface temperature. Alternatively, for a given surface temperature, the presence of electric field, significantly increases the heat flux. The electric field reduces the contribution of latent heat transport to the total heat flux, primarily, due to the reduction in the number of active nucleation sites. The reduction in latent heat transport especially at low heat fluxes produces a commensurate reduction in the forced convection contribution to the total heat flux.

In convective boiling, a relation between electro-hydrodynamic pressure and momentum flux rate was derived ([9]). Enhancement of heat transfer in this case is significantly influenced by quality, flow regime, heat flux and mass flux and all three components of EHD force densities in Eq. (1) will be present, however the second term, electro-strictive force, is expected to dominate as the quality and heat flux increases. From the experimental data it is evident that the EHD forces can generate significant enhancement in convective boiling heat transfer coefficient, but at the same time, they can create even greater pressure drop penalties. It may also cause the suppression of the heat transfer coefficient depending on the value of the quality, heat flux, and applied potential ([9]). An interesting result from a stability analysis showed that the transition of the effect of electric field from enhancement of heat transfer to suppression of it, took place close to the annular to mist flow regime transition ([1]).

Evaporation: Experiments shown that electric field applied to vertical falling film evaporation of R-123 enhanced heat transfer effectively by retaining the liquid, distributing the liquid film flow and thinning the liquid film. There is an optimum voltage at which the evaporation heat transfer coefficients are maximized. Above this level, EHD forces promote dry patch formation on the tube surface, which then decreases the heat transfer efficiency. In the best results have reached, Evaporation heat transfer was enhanced six-fold over that for smooth tubes by using electrodes made of punched-out plates of vertically arrayed offset fins ([10]). Fig. (2) shows the enhancement ratio versus applied voltage for a specific enhanced tube with applied voltages of 20, 15 and 10 kV with R-134 as dielectric fluid ([11]).

In the long term use tests of EHD evaporator, small amounts of carbon, aluminum and silicon adhere to the surface of the heat transfer tube after 1000 hours of operation, but are low enough so that these types of EHD heat exchangers are suitable for industrial application.

Condensation: Only a few researches were found in the field of EHD enhancement of condensation. An experiment done by *Seth and Lee* [12] with some mixtures of R-113 and air, shows that by application of an electric field the separation rate of a drop become less while the number of drops increased. The presence of noncondensable gases in the bulk refrigerant vapor with or without an electric field decreases the film condensation heat transfer, and the electric field can be used as a means to overcome the poisoning effect of non-condensable gases when only a small fraction of such gases are present.

3.2. Single Phase Processes

Electric fields can be utilized to increase heat transfer coefficient in free convection. The configuration maybe similar to that in the phase change processes, a heated wire with a lattice type rectangular electrode maintained at a high voltage relative to the wire, or a fine wire electrode maybe utilized with a horizontal plate, or any different geometry. Here, EHD forces causing greater bulk mixing in the vicinity of the heat transfer surface.

Researches of *Kronig and Schwarz* [13] lead to development of a characteristic electrical number, *El*, analogous to the Grashof number in buoyant convection. The non-dimensional electrical number was used to define an electric Rayleigh number:

$$Ra_{El} = El \times Pr \tag{2}$$

This in turn was used to describe the enhancement of natural convection in gases. The electrical number is a ratio of electric forces to the viscous forces ([14]). The model was corrected for liquids by using a modified electrical number for uniform electric fields, assumes that dielectrophoretic term in Eq. (1) is dominant ([15]). finally, *Pauscal* [16] corrected the electrical number again and this corrected one is:

$$El_{Corrected} = \left[1 + \frac{1}{2} \frac{\varepsilon + 2}{\frac{d\varepsilon}{dT} \Delta T} \frac{D}{L_2} \right] \times El \tag{3}$$

Where:

$$El = \frac{\rho \frac{d\varepsilon}{dT} D^2 \Delta T_0 E^2}{\mu^2} \tag{4}$$

L_2 represents the length scale associated with the divergence of the electric field.

Pascaul et al. [14] developed an equation based on experiments from different designs, electric field strengths and electric field geometries and present the following equation for the amount of increased heat transfer in the form of Nusselt number:

$$\Delta Nu = 0.0895 Ra_{El}^{0.365} \tag{5}$$

The correlation was applicable over a range of electric Rayleigh number from 4×10^3 to 8×10^8 with either a uniform or nonuniform electric field.

In gases, electrophoresis forces, with some special electrode geometries, can be used to improve heat transfer from a heated plate. This method involves the corona wind phenomenon that occurs in gases with a high voltage small diameter or needle type electrode placed above the plate. Analysis by *Steutzer*[17] and *Robinson*[18] resulted in a basic understanding of the fluid mechanics of the phenomenon and *Marco and Velkoff* [19] were the first to examine the application of the corona wind to heat transfer enhancement. According to the theory developed by *Steutzer* and *Robinson*, higher voltages must lead to increased pressure generation and fluid velocity. Higher fluid velocity, of course, leads to great heat transfer. However the experiments with air as shown in the Fig. (3) indicate that increased voltages improved the maximum local heat transfer coefficient only to a certain point. Beyond this point further increase in voltage actually decreased the observed enhancement near the impingement point of the induced flow ([20]).

Two phenomena are mentioned as responsible for this apparent violation of theory ([20]): joule heating of the air and entrainment inefficiency. Joule heating leads to a decrease in effective impingement point local heat transfer coefficients, since the heated corona wind simply cannot cool the surface as much as an unheated flow.

Additionally, at very small needle heights, inefficient entrainment of natural unheated air reduces the heat transfer coefficient severely.

Despite increased power consumption, the negative corona wind generated less joule heating than the positive one. Therefore at a constant voltage, the negative corona wind generates a slightly higher impingement point heat transfer coefficient. Heat transfer enhancement can be optimized by proper selection of the needle-plate gap distance and applied potential. Efficiency greatly reduces when the needle plate gap distance is too small. However efficiency does not change significantly with increasing height once the needle gap increase beyond a threshold.

4. Applications and Research Programs

As indicated, heat transfer augmentation and enhancement with EHD effects was studied in several cases and researches continue to find the optimum condition and geometry for the applicability of this method. A big current obstacle for the employment of EHD technique to applications such as air conditioning and refrigeration equipments seems to be a more complicated manufacturing process required for the electronics needed and its increased material cost. Of course, an advantage of utilizing such a method is that the heat transfer performance can be easily controlled by varying the applied voltage and if more effective augmentation of heat transfer by EHD technique becomes practical, present heat exchangers will be replaced by ones which use EHD in many fields. The expected area of application is a thermal control system in a space station where due to a large amount of exhaust heat, a two phase thermal control system is needed. However there are serious problems with two phase heat transfer in space. Because of reduced gravity the specific weights of liquid and vapor become equal and the bubble generated during boiling can not be smoothly removed from the boiling surface, which can cause deterioration of heat transfer. In order to solve this problem, electric forces are promising replacements of gravity ([7], [21]).

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6. Nomenclature

D	Heat transfer surface diameter (m)
E	Electric field strength (V/m)
El	Electrical number
$El_{corrected}$	Corrected electrical no. for liquids
F	Force density (N/m^3)
h_{loc}	Local heat transfer coefficient ($W/m^2.K$)
h_0	Heat transfer coefficient without EHD effect ($W/m^2.K$)
L_2	Characteristic length of the electric field divergence (m
Pr	Prandtl number
Ra_{El}	Electric Rayleigh number
T	Temperature (K)

Greek symbols

ρ	Density (kg/m^3)
ρ_f	Electric charge density (C/m^3)
ε	Electric permittivity (F/m)
μ	Dynamic viscosity (kg/m.s)

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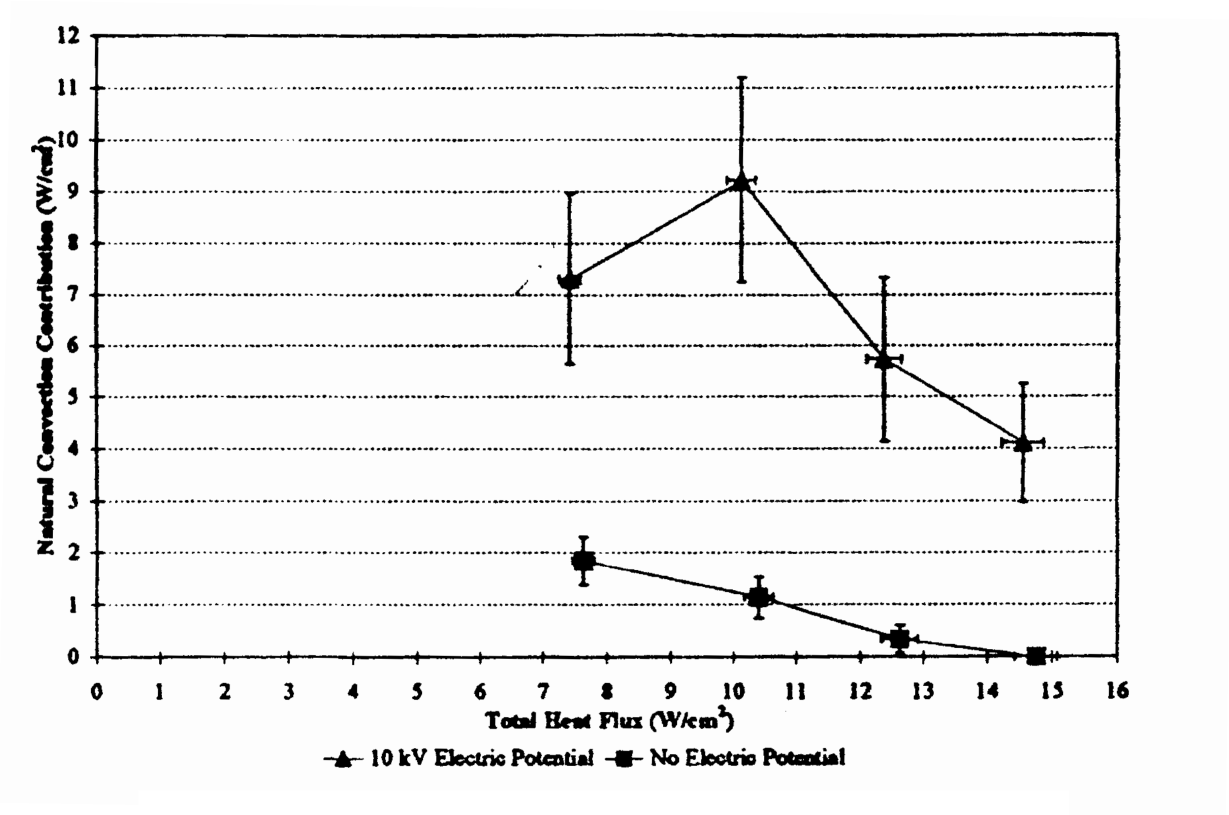

Fig. (1): (a) Relative heat flux contributions for experiments with no electric field. (b) Relative heat flux contributions for experiments with 10 kV electric potential ([3]).

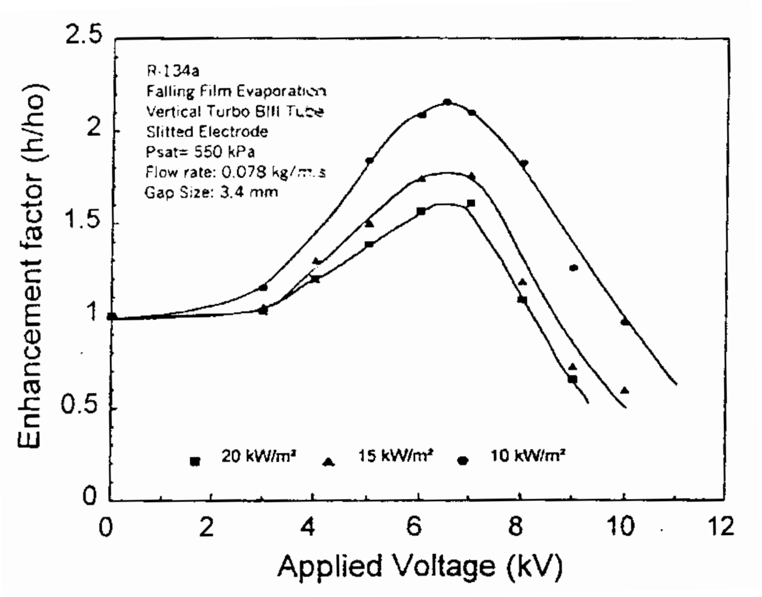

Fig. (2): Enhancement factor versus applied voltage on a Turbo Bill tube and a silted electrode ([11]).

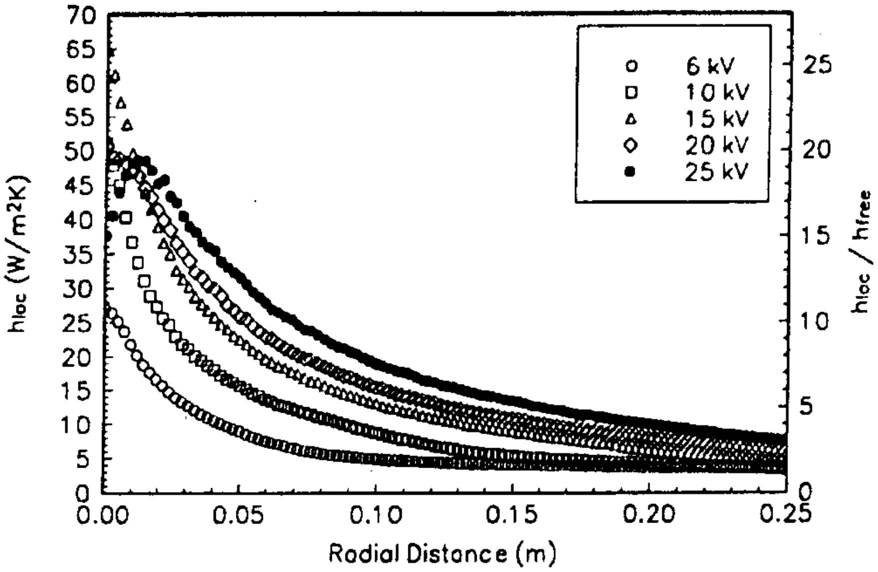

Fig. (3): Local heat transfer coefficients with various voltages and needle height of 5 cm ([20]).