Heat Transfer Enhancement using Electric Fields

A Report on Mini Project – I

Submitted in Partial Fulfillment of Requirement for the Degree of B. Tech. in Mechanical Engineering

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Contents

1. Abstract

The present article consists of a detailed literature review on how Electric field can be used to enhance the heat transfer in various ways possible. It discusses about how the force acting on a dielectric fluid can be exploited to enhance Heat Transfer. The importance of the Placement and Design of the electrodes have been discussed in great detail. The use of EDH in boiling and Condensation have also been discussed along with Electric field enhancement techniques in Gas and Liquid phase. Heat can be transferred using electric field and the force exerted add a term to the momentum which influences fluid motion.

2. Introduction

Scientists and researchers were keenly interested in systems for heat exchange. The reason behind this is that in everyday life and industries it has wide applications. Heat exchangers, boilers, condensers, radiators, heaters, furnaces, cooling towers, solar collectors, heating, ventilation and air conditioning (HVAC) devices utilizing heat exchangers. The primary beneficiaries of heat exchangers are the automotive industries, chemical industries, petrochemical industries, and refrigeration industries.

Each industry has heat transfer processes for different operations, both small and large. Using heat transfer enhancement techniques makes heat exchangers compact and efficient, but increases cost proportionally at the same time. The heat exchanger's viable adaptation has been the hotspot for the past two decades. The researchers review the techniques from time to time in order to achieve better performance and optimized designs.

There are 13 heat transfer enhancement techniques[1] available. Some basic techniques are surface coatings, extended surfaces such as fins, rough surfaces, coiled tubes, square and helical ribs, electrostatic fields, and surface vibration. The methods of enhancement were generally categorized into two groups: the active technique and the passive technique. These will be discussed later, in detail.

Heat transfer enhancement refers to Application of basic concepts of heat transfer processes to improve the rate of heat removal all deposition on a surface. The process industry is aggressively working to incorporate enhanced heat transfer surfaces in its heat exchangers. Virtually every heat exchanger is a potential candidate for enhanced heat transfer . However each potential application must be tested to see if enhanced heat transferred “make sense”. Heat exchangers where initially developed to use plain or smooth heat transfer surfaces .An “enhanced heat transfer surface” has special surface geometry that provides higher hA value, per unit base surface area than a plain surface.

Thus, Enhancement ratio = hA /(hA) p.

Q = UAΔTm

The performance of heat exchanger will be enhanced if the term kA/l Is increased. An enhanced surface geometry maybe use to increase either or both of hA /l terms, relative to that given by plain surface. This will reduce the thermal resistance per unit tube length, l/hA. This reduced l/kA may be used for one of 3 objectives: 1 size reduction 2 increased kA 3 reduced pumping power for fixed heat duty Size reduction: if the heat exchanger rate is held constant the heat exchanger length may be reduced. This will provide a smaller heat exchanger.

Increased kA : this may be exploited either of two ways ReducedΔ Tm: if the total tubelength and are hold constant the team may be reduced. This provides increased thermodynamic process efficiency and yields a saving of operating costs. Increased heat exchange :Keeping l constant the increased by kA/l will result in increased heat exchange rate for fix fluid inlet temperature.

3. Heat Enhancement Using Electric Fields

Heat Enhancement using Electric Fields

Heat can be transferred using electric field. Application of an electric field to a dielectric fluid imposes a body force on the fluid. This body force adds a term to the momentum equation and influences the fluid motion. It must be noted that the fluid be a dielectric and thus not conduct any electricity. This body force used in the Navier-Stokes equations is described by the change of Helmholtz free energy for virtual work with the energy stored in fluid by the electric field.

Electrohydrodynamics(EDH) is recognized as a technology with high energy efficiency. The Electrohydrodynamic (EHD) augmentation technique utilizes the effect of electrically induced secondary motions to destabilize the thermal boundary layer near the heat transfer surface, leading to heat transfer coefficients that are often an order of magnitude higher than those achievable by any of the conventional enhancement techniques.

The electrohydrodynamic (EHD) technique utilizes the effect of electrically induced secondary motions, when a high-voltage, low current electric field is coupled with the flow field in a dielectric fluid medium. For boiling applications, the net effect is a substantial increase in the boiling dynamics near the heat transfer surface, leading to heat transfer coefficients that are often an order of magnitude higher than those achieved with any of the conventional passive or active enhancement techniques. As described by Panofsky and Phillips [1962], application of electric field strength E to a constant-temperature dielectric fluid of permittivity, ε and density ρ results in F_e given by

$$F_e = \rho_c E - 0.5E^2 \nabla \varepsilon + 0.5E[pE^2 (\partial\varepsilon/\partial\rho)] \quad \ldots. (1)$$

The electric field strength will vary with distance from the electrode, and depends on the electrode design. The physical significance of the three terms in equation (1) are as follows: -

1. The first term is the electrophoretic force acting on the net free charge of electric field space charge density, ρ_c. The direction of the force depends on the relative polarities of the free charges and the electric field.
2. The second term is the "di-electrophoretic" force produced by the spatial change of permittivity, ε. In two-phase flow, this force arises from the difference in permittivity of the vapor and liquid phases.
3. The third term is called the "electrostriction" force and is caused by inhomogeneities in the electric field strength and may be linked to an "electric pressure".

The electric current due to this force is given by

$I = \rho_c u + \sigma_e E$ … (2)

where u is the fluid velocity, and σ_e is the electrical conductivity of the fluid. In steady state, without convention, the electric charge density is given by

$\rho_c = - \varepsilon E \nabla \sigma_e / \sigma_e$ … (3)

So, it can be inferred that the electric charges are generated by the gradient of the electrical conductivity. The electrical conductivity of the liquid is temperature dependent; equation (3) shows that temperature gradients in the fluid generates the electric charge. This makes the Colomb Force – an Active Force.

The momentum and energy equations are coupled through the temperature dependence of the permittivity and thermal conductivity of the fluid. Cooper showed that the coupled momentum and energy equations is not possible unless in very simple cases. Rather, data are correlated on the basis of the predicted electric field strength distribution at the heat transfer surface on the basis of uniform electrical fluid properties.

4. Benefits of Heat Transfer Enhancement

The heat transfer enhancement is required for heat-exchanging devices. For convective heat transfer mode, the basic heat transfer equation is given by

$$Q = hA\Delta T \qquad (3.1)$$

where Q is the rate of heat transfer, h is the convective heat transfer coefficient and ΔT is the temperature difference. Heat transfer enhancement ratio, E_r, is the ratio of the *(hA)* of an enhanced surface to that of a plain surface or basic surface.

Thus,

$$E_r = \frac{hA}{(hA)_p} \qquad (3.2)$$

The rate of heat transfer for a constant temperature difference can be increased by two ways:

(a) Increasing "h" without changing physical area (A)

(b) Increasing heat transfer surface area (A) without changing "h"

© Increasing both "h" and "A"

For the enhanced surface, the thermal resistance per unit tube length is reduced and this can be used for one of the three purposes: size reduction giving a smaller heat exchanger, increased conductance which will give reduced temperature difference and increased thermodynamic process efficiency and this finally gives a savings of operating cost. Also, there will be increased heat exchange rate for fixed fluid inlet temperatures. Thirdly, pumping power can be reduced for fixed heat duty when the heat exchanger operates at a velocity smaller than the competing plain surface. This requires increased frontal area which is a negative effect.

The first case can be taken care of by surface roughness inside tube, duct, etc., whereas the second case can be achieved with finned tubes. The third case can be dealt with by using fins with coils, screw tapes, etc. These techniques result in heat transfer enhancement many times for the same pressure drop. In some cases, researchers have even found 300% increase in heat transfer rate over that in a plain tube. However, it should be kept in mind that all geometries are not practical due to the difficulty in manufacturing complex geometries using required materials.[3]

5. Industrial Importance

The technical and economic indicators of thermal power installations are determined to a considerable degree by the parameters of heat exchangers. Such apparatuses have very significant mass and volume. An increase of the capacities of single power installations, which is the main trend in their development, entails a growth in the absolute mass and dimension character istics of HEs used in these installations. Accordingly, the problem of improving heat exchangers in terms of decreasing their dimensions and mass (metal inten sity) and reducing the power required for pumping heat carriers through the apparatus while retaining their thermal capacity is becoming more important and topical. It is obvious that at present and the future, one of the main ways—most accessible and justified in tech nical and economic respects—in which the mass of power installations can be decreased and more effi cient operation of them can be achieved consists of improving HEs, which can be achieved through the use of efficient methods for enhancing heat transfer.

The objective of the present research is to quantify the applicability and limitations of the EHD technique for boiling and condensation heat transfer enhancement of alternate refigerantshefigerant mixtures. This will include experiments that will address two distinct issues: (1) determine the extent by which the EHD technique can enhance the heat transfer characteristics of alternate refrigerantshefiigerant mixtures, (2) determine any long term effects the EHD technique may have on the characteristics of the refiigeranthystem, including aspects such as additional fouling effects, potential degradation of the refrigerant; reliability of the electrode system for continuous operation; and the economics of the technique in terms of added capital and operational cost. With these objectives in mind, the test rigs have been designed and fabricated such that both low and high pressure refrigerants can be tested. Of particular interest is to identify optimum conditions for maximum enhancement with minimum additional electrical power consumption. The overall goal of the project is to collect basic and application oriented data that will lead to development of EHDenhanced, high-performance, advanced evaporators and condensers.

A great number of patents on heat transfer enhancement have become the result from commer cialization of methods for enhancing heat . A large number of coefficients that take into account economic (expenditures for devel opment, construction, operation, maintenance, etc.) and production factors (suitability surfaces for machineaided processing, assembling, mounting of devices and other production processes), reliability (compatibility of media and materials, stiffness of structures and their service life), safety, etc. must be taken into consideration in solving this problem apart from relative thermal–hydraulic efficiency of heat transfer intensifiers. In the majority of cases, the developers of HEs who use methods of heat transfer enhancement pursue the following objectives apart from fulfilling technical specifications and achieving the specified working characteristics of heat exchangers: (1) Increasing the thermal capacity of existing heat exchanger without changing the power required for pumping heat carriers (or pressure losses) at fixed flowrates of heat carriers. (2) Reducing the temperature difference between heat carriers for achieving the specified thermal capacity at fixed overall dimensions of a heat exchanger. (3) Decreasing the mass and dimension character istics of a heat exchanger while preserving its thermal capacity and pressure losses in its paths. (4) Decreasing the power required for pumping heat carrier with fixed thermal capacity and retaining the heattransfer surface area. Objectives (1), (2), and (4) relate to energy conser vation and objective (3) relates to the task of saving resources (reduction of metal intensity and cost). The approach of the authors of this paper to this question is described in [14]. In fact, methods of heat transfer enhancement are aimed at reducing the thermal resistance of nearwall layers during convective heat transfer in a heat exchanger and help increase the coefficient of heat transfer with or without increasing the working surface of the apparatus. Sixteen different methods of heat transfer enhancement were classified in [1–3] and subdivided into passive ones (no external supply of energy is required for enhancement), active ones (requiring some amount of external power supply), and complex ones (see the table).

Enhancement methods	Principle of action
Active	Mechanical mixing Surface vibration Flow pulsation Electrostatic fields Injection Suction of boundary layer Jet apparatuses
Passive	Finished surfaces Rough surfaces Extended surfaces Mixing devices Flow swirlers Coils Surface tension devices Admixtures for liquids Admixtures for gases
Complex	Two or more passive and/or active meth-ods simultaneously

Heat transfer enhancement techniques have a wide range of commercial applications. They include heat exchangers; cooling towers; cooling units; heating, ventilation and air conditioning; distillation columns; etc. Heat and mass transfer occur simultaneously in some devices, such as cooling towers and distillation columns. Commercially, heat transfer enhancement techniques are used for heat exchangers and this book focuses on the same thing. The heat exchangers are classified into four main groups:

- Shell-and-tube heat exchangers or tube banks
- Fin-and-tube heat exchangers
- Plate-fin heat exchangers
- Plate-type heat exchangers

6. Classification of Heat Enhancement Techniques

Different techniques have been used for the enhancement of convective heat transfer over the years, being upgraded according to technological developments. The heat transfer technology used in industries can be classified into three generations which have been presented in Table 1.[4]

The heat transfer techniques of the first generation commonly used bare tubes, the second generation advanced to plain fins, the third generation moved to fins and extended surface vortex generators, and the fourth generation moved to compound enhancement techniques. The enhancement strategies for heat transfer were classified into two classes, active techniques and passive techniques. Compound enhancement techniques are the sum of two or more active or passive techniques. Compared to individual techniques, the heat transfer performance using compound techniques improves tremendously.

A great deal of work on heat transfer enhancement strategies has been published in the literature. As the number of papers on heat and mass transfer enhancement has increased rapidly over the years, Bergles and Manglik (2013) published a detailed review addressing both single-phase and two-phase heat transfer enhancement phenomena, reviewing the literature on active, passive and compound techniques. The classification of different heat transfer increase techniques has been shown in Table 2. [5]

Table 3 shows these techniques with their relevance. Thus, enhancement techniques, either active or passive or compound techniques, reduce the operating cost by large amount. However, passive techniques are more significant over active techniques as active techniques are relatively noisy, their reliability is less, they are little costlier and they have safety issues.[6] We shall explore these two types of heat transfer techniques further, in the later section.

Table 1: Three generations of heat transfer technology [4]

Tube-and-plate fins, single phase	
First generation	Bare tube
Second generation	Plain fins
Third generation	Longitudinal vortex generators on fins
In-channel, single phase	
First generation	Smooth channel
Second generation	2-D roughness
Third generation	3-D roughness
Outside tubes, boiling	
First generation	Smooth tube
Second generation	2-D fins
Third generation	3-D fins and metallic matrices
In-tube, evaporation	
First generation	Smooth tubes
Second generation	Massive fins and inserts
Third generation	Micro-fins
Outside tubes, condensing	
First generation	Smooth tubes
Second generation	2-D fins
Third generation	3-D fins and metallic matrices

Table 2: Classification of heat transfer augmentation techniques [5]

Passive Techniques	*Active Techniques*
Treated surfaces	Mechanical aids
Rough surfaces	Surface vibration
Extended surfaces	Fluid vibration
Displaced enhancement devices	Electrostatic fields
Swirl-flow devices	Injection
Coiled tubes	Suction
Surface tension devices	Jet impingement
Additives for liquids	
Additives for gases	
Compound Techniques	
Two or more passive and/or active techniques used together Wavy plate-fins with punched-tab vortex generators Rotating internally finned tubes	

Table 3: Active enhancement techniques [6]

	Single-phase natural convection	Single-phase forced convection	Pool boiling	Forced convection boiling	Condensation	Mass transfer
Active techniques (external power required)						
Mechanical aids	16	60	30	7	23	18
Surface vibration	52	30	11	2	9	11
Fluid vibration	44	127	15	5	2	39
Electric or magnetic fields	50	53	37	10	22	22
Injection or Suction	6	25	7	1	6	2
Jet impingement	-	17	2	1	-	2
Compound techniques	2	50	4	4	4	2
Note: – not applicable; + no citations located						

7. Active Techniques

Active techniques require external power sources such as electrical field, acoustic field and ground vibrations to facilitate heat transfer. Mechanical aids used to move liquids by any mechanical means shall also be subject to effective techniques. Equipment combined with revolving heat exchanger ducts are commonly used in factories to improve heat transfer. Surface vibration technique with different frequency ranges has been used to improve the rate of heat transfer. The movement propels the small droplets to the hot layer where thin-film evaporation happens. The impingement of small droplets promotes "spray cooling." Electrostatic forces are used for greater mass mixing of dielectric fluid. Jet impingements, bubble injection, fluid vibration and magnetic field manipulation are some other active techniques.

One of the active techniques is the use of electrohydrodynamic (EHD) forces for heat transfer enhancement. Theoretical and experimental studies accounted for the wire electrode position, primary velocity and applied voltage for results. They discussed the potential application of ionic wind and visualised the flow pattern with a series of wire electrodes installed parallel as well as perpendicular to primary flow direction.[7] Another study which adopted electrohydrodynamic active enhancement technique, investigated experimentally the effect of electric field on an inclined heated plate by using convective heat transfer mode and showed that by increasing the applied voltage, EHD heat transfer coefficient increases. (Figure 2) [8]

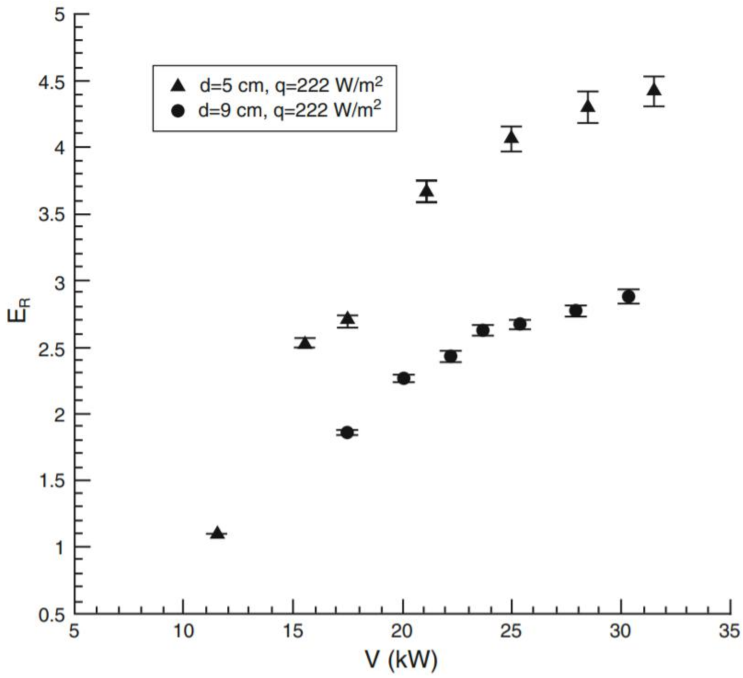


Figure 2: Effect of applied voltage on enhancement ratio [8]

Another research experimentally studied the free and forced convective heat transfer induced by the motion of the copper sphere. They found that, for free convection, the influence of vibration on the Nusselt amount was significantly higher than (unto seven times) the value obtained by free convection without vibration.[9]

Another group of researchers focused on heat transfer enhancement of the heated cylinder conjugated with multi-orifice synthetic jet impingement and contrasted their own findings with those of others. They compared the flow characteristics with the piccolo tube and the heated cylinder and calculated the Nusselt number for the heated cylinder with the time and observed 2-3 times higher heat transfer rates than those without jets. They also concluded that the performance of the upward direction jet was good and that the deep efficiency of the synthetic jets was achieved when they were placed at a distance greater than that of the continuous jets. Figure 3 shows the variation of average Nusselt number with the distance between orifice and cylinder for synthetic jets and continuous jets which favour the results. [10]

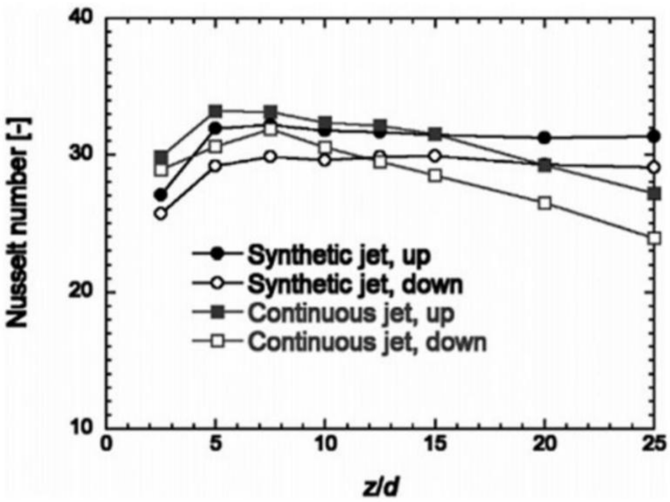


Figure 3: Comparison of jets [10]

Another team was focusing on the numerical simulation of the convective heat transfer enhancement with three different configurations of the jet impingement cooling porous frame. Specific spatial arrangements, coordinate framework and three separate porous obstacle locations with jet impingement cooling system are shown in Fig. 4. Numerical studies were performed with three different configurations of jet impingement with a porous block as a heat sink in the stagnation region, as a flow barrier along the bottom plate and as a flow barrier along the top plate away from the stagnation area. Simulated results show that convective heat transfer can only be increased in the event of flow barriers along the upper bounding wall away from the stagnation region. However, it was not clear whether the improvement was due either to porous heat sink barriers on its own or to variations in the geometric parameters used for comparison.[11]

Another study investigated the enhancement of heat transfer using bubble injection, which is one of the active heat transfer augmentation techniques. They investigated the heat transfer enhancement in a thermal storage tank with air bubble injection. They reported that the enhancement in overall heat transfer between the storage fluid and the environment had increased five times and that between the storage fluid and the heat transfer fluid had increased two times.[12]

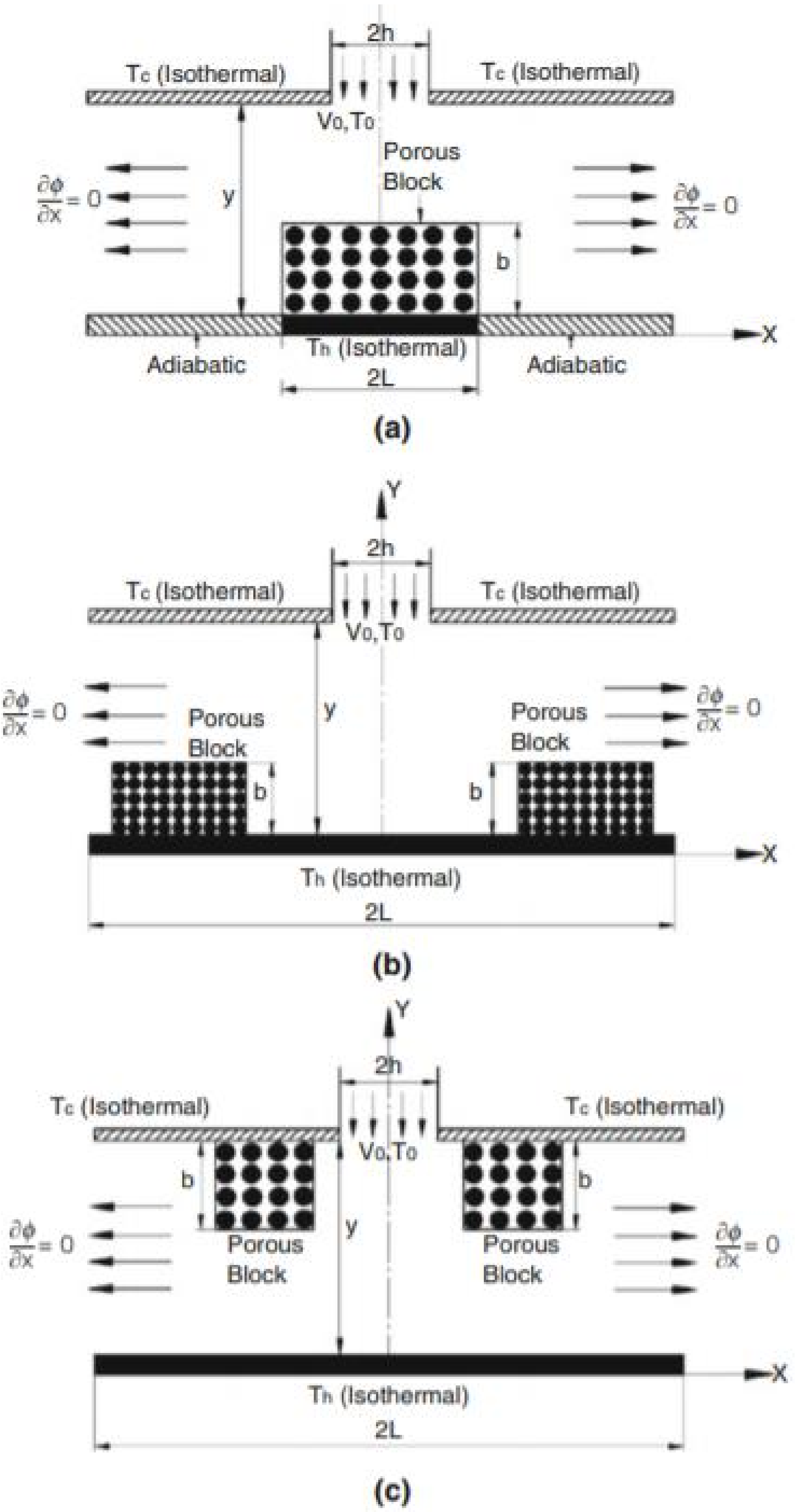


Figure 4: Jet impingement with porous media (a) as porous heat sinks, (b) as flow obstacles along the bottom plate and (c) as flow obstacles along the top wall [11]

8. Design and Placement of Electrodes

The design and the placement of the electrodes is important to enhance EDH. The design and location of the electrodes depend on whether the flow is single- or two-phase. Also, they depend on the thermophysical and electrical properties of the fluid. The position of the electrodes must be such as that the electric field force aids the hydrodynamic forces, particularly at the heat transfer surface. For separated two- phase flows, the permittivity of the liquid and vapors will be distinctly different. Hence ∇E exhibits a singularity at a liquid-vapor interface. Jones [1978] shows that the fluid component having the highest E will move to the region of highest field strength, *E.* A liquid drop will move toward the electrode, and a bubble will move toward the region of lower field strength.

Placement of the electrodes is different for tube-side and shell-side heat transfer enhancement. Consider heat transfer to a fluid flowing inside a tube. Figure 1 shows a wire electrode in the center of a tube. If the fluid inside the tube has constant permittivity (E), the field strength distribution for this configuration is given by: -

$$E = \{V[\ln(R_1/R_2)]^{-1}\}/R \qquad \dots (1)$$

where *V is* the applied voltage, *r* is the radial distance from the tube axis, and *R1* and *R2* are defined in Figure 15.1. The field strength decays with radial distance from the central electrode wire. If a liquid-gas mixture flows in the tube, the liquid phase will have the highest permittivity. Hence, the liquid will move toward the central electrode, leaving vapor at the tube wall. This will enhance condensation, but not evaporation, which requires liquid at the tube wall. Condensation enhancement would occur, because the electrode pulls condensate away from the Condensing Surface. Figure 2 shows electrode designs used by Cooper [1992] for enhancement of shell-side boiling in a tube bundle. Figure 3 illustrates electrode designs used by Yabe et al. [1987], for enhancement of condensation on the outer surface of vertical tubes. The Figure 3 electrodes produce a non-uniform electric field. Both ac and de voltages provide enhancement.

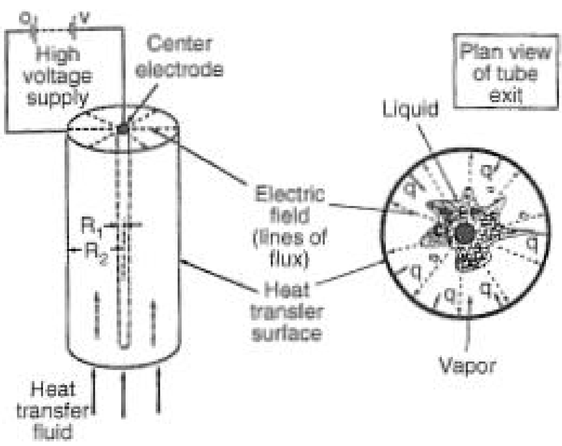


Figure 15.1 Wire electrode in center of tube with two-phase flow. (From Cooper [1992].)

The enhancement effect will be increased by increasing the applied voltage. The electrical breakdown strength of the liquid and vapor must be known and should not be exceeded. As noted by Cooper [1992], careful design of the solid insulation system is required. Poor design may result in electrical breakdown, which would make the EHD enhancement system useless. The insulation material must be compatible with the heat transfer media. Inert dielectrics, such as PTFE and proprietary epoxy composites, are candidates. Cooper [1992] notes that high electric stress exists near small radii of curvature on solids, so electric breakdown may occur at these locations. Electrode and insulation surfaces should be rounded and conducting rods of large radius should be used to reduce the local electrical field strength. Design aspects of the insulation system are discussed in texts on power transformers and switchgear, such as Kuffel and Zaengl [1984].

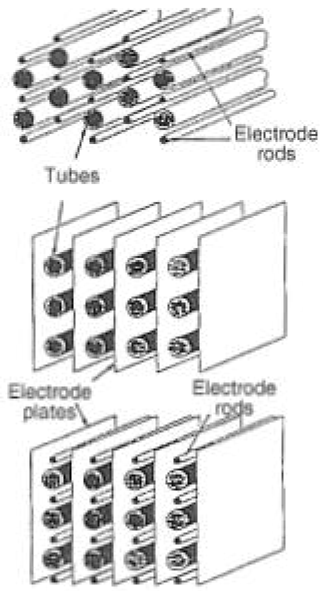


Figure 15.2 Electrode designs used by Cooper [1992] for enhancement of shell-side boiling in a tube bundle. (From Cooper [1992].)

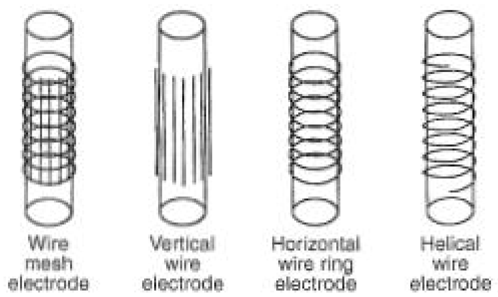


Figure 15.3 Electrode designs used by Yabe [1987], for enhancement of condensation on the outer surface of vertical tubes. (From Yabe [1987].)

Voltages up to 25 kV are typically used in EHD enhancement. Although high voltages are used, the electric current is quite small (e.g., 1 mA) and thus the power consumption is small. To place these voltages in perspective, automotive spark plugs, and electronic air cleaners operate at approximate voltages of 25 and 10 kV, respectively. The power is supplied by a relatively low kVA power supply consisting of a high-voltage transformer operating at very small current. A device, such as an automotive spark plug, may be modified to bring the high-voltage supply conductor through the heat exchanger wall. The use of very small currents minimizes physical hazards. All high-voltage surfaces are completely contained within the heat exchanger, which is electrically from the shell and the tubes. Provided that adequate insulation is used, no danger of electric shock should exist.

Laohalertdecha et al. (2007) reviewed the electrohydrodynamic techniques required for the enhancement of heat transfer. This active technique requires coupling of an electric field with the fluid field applied in a dielectric fluid medium. In this technique, DC or AC high-voltage low current is typically used. The EHD force (Fe) developed due to flow of charge between charged and grounded electrode is presented as

$$F_e = \tfrac{1}{4} qE - \{E^2(\nabla\varepsilon)\}/2 + \{\varepsilon_o(K-1)(K+2)(\nabla E)^2\}/6 + \{\varepsilon_o E^2 \nabla[(K-1)(K+2)]\}/6 \quad \text{.... (2)}$$

where K is relative permittivity, ε and ε_o are electric permittivity of fluid and vacuum, respectively. They reviewed the EHD enhancement technique in both single-phase transfer and two-phase transfer. They provided two tables: the first one was for EHD enhancement of condensation (Table 2.1) and the second one refers to EHD enhancement of boiling (Table 2.2). This review presents a better idea for EHD techniques for condensation in horizontal tube and boiling in horizontal and vertical tubes, but no literature has reviewed condensation in vertical tube using EHD techniques. Dulikravich and Colaco (2004) presented convective heat transfer characteristics under the influence of magnetic and electric fields. For many years, the application of electric and magnetic fields has been used in magnetohydrodynamic pumping, electrohydrodynamic pumping and electromagnetic stirring of molten metal. The parameters for Navier–Stokes equations and Maxwell's equations for a standard MHD model have been tabulated in Table 2.3. Similarly, the corresponding parameters for EHD models have been listed in Table 2.4. The various optimization models of magnetic and electric fields available are differential evolution algorithm, quasi-Newtonian Pshenichny-Danilin algorithm, genetic algorithm, Davidon– Fletcher–Powell gradient search algorithm and modified Nelder–Mead simplex algorithm.

Thus, the use of properly designed of Electrodes plays an important role in the enhancement of EDH.

Table 2.1 EHD enhancement of condensation (Laohalertdecha et al. 2007)

Source	Working fluid	h_{EHD}/h_o (max)
Bologa and DidKovsky	Diethyl ether	20
	R-l13, hexane	10
	Diethyl ether	20
Bologa et al.	Hexane-carbon dioxide	5
Bologa et al.	Freon-113	~20
Bologa et al.	R-l13-helium	1.8
	R-l13-air	2.6
	R-l13-carbon dioxide	3.0
	Hexane-air	5.0
Butrymowicz et al.	R-123	~2
Cheung et al.	R-l34a	7.2
Choi	Freon-R-113	2
Choi and Reynold	R-l13	2
Cooper and Allen	R-12 and R-l14	2.9
Damianidis et al.	R-l14	I.08
Didkovsky and Bologa	Non-polar and polar dielectrics	20
Holmes and Chapman	R-l14	Up to 10 times
Jia-Xiang et al.	Freon-11	~1.85
Seth and Lee	R-l13	1.6
Silva et al.	R-l34a	~3
Singh et al.	R-l34a	6.5
Smirnov and Lunev	R-l13, diethyl ether	3.6
Sunada et al.	R-123	~6
Trommelmans and Berghmans	R-l1, R-13 and R-l14	1.1
Velkoff and Miller	Freon-R-113	1.5
Wawzyniak and Seyed-Yagoobi	R-l13	6.1
Yabe et al.	Water, R-l13	2.24
Yabe et al.	Silicone oil, R-l13	4.5
Yamashita et al.	C_6F_{14} (perfluorohexane)	6
	R-l14	6
	n-Perfluorohexane	4

Table 2.2 List of the EHD enhancement of boiling (Laohalertdecha et al. 2007)

Source	Working fluid	h_{EHD}/h_0(max)
Allen and Cooper	R-114	Up to 60
Blachowicz et al.	Benzene	2
Bochirol et al.	Trichlorethylene and ethyl ether	2.7
	Methyl alcohol	6
Cheung et al.	R-134a	5.1
Cooper	R-114 + oil	13
Damianidis et al	R-114 (smooth tube)	~1
	R-114 (low-fin tubes)	2.5
Feng and Seyed-Yagoobi	R-134a	~4.5
Kawahira et al.	R-11	4
Karayiannis	R-123 and R-11	9.3
Karayiannis et al.	R-114	4
Liu et al.	R-123	2.1
Neve and Yan	R-114	3
Ohadi et al.	R-123	5.5
	R-11	1.7
Ogata et al.	R-123	7
Papar et al.	R-123	6
Schnurmann and Lardge	*n*-Heplane	~7
	20% solution of isopropyl alcohol in *n*-heptane	~7
	Perfluoromethylcyclohexane	~2
Watson	*n*-Hexane	2.6
Source	R-123 + R-134a	3
Yabe et al	R-123	6
Yamashita and Yabe	Acetone, benzene	1.82
Zheltukhin et al.	*n*-Diethyl ether	(acetone)

Table 2.3 Parameters for the Navier–Stokes and Maxwell's equations in a standard MHD model (Dulikravich and Colaco 2004)

Conservation of	λ	ϕ	ϕ^*	ϕ^{**}	ϕ^{***}	Γ	S
Mass	ρ	1	1	1	1	**0**	**0**
x-Momentum	ρ	u	u	u	u	μ	$-\frac{\partial p}{\partial x} - \frac{B_y}{\mu_m}\left[\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}\right]$
y-Momentum	ρ	v	v	v	v	u	$-\frac{\partial p}{\partial y} - \rho g\left[1 - \beta(T - T_o)\right) + \frac{B_x}{\mu_m}\left[\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}\right]$
Energy	ρ	h	h	h	T	k	$\frac{1}{\sigma\mu_m^2}\left[\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y}\right]^2$
Magnetic flux in *x*-direction	1	B_x	**0**	B_x	B_x	$\frac{1}{\mu_m\sigma}$	$\frac{\partial(uB_y)}{\partial y}$
Magnetic flux in *y*-direction	1	B_y	B_y	**0**	B_y	$\frac{1}{\mu_m\sigma}$	$\frac{\partial(uB_x)}{\partial x}$

Table 2.4 Parameters for the Navier–Stokes and Maxwell's equations in a standard EHD model (Dulikravich and Colaco 2004)

Conservation of	λ	ζ	ϕ	ϕ^*	ϕ^{**}	ϕ^{***}	Γ	S
Mass	ρ	0	1	1	1	1	0	0
x-Momentum	ρ	0	u	u	u	u	μ	$-\frac{\partial p}{\partial x}+q_e E_x$
y-Momentum	ρ	0	v	v	v	v	μ	$-\frac{\partial p}{\partial y}-\rho g[1-\beta(T-T_o)]+q_e E_y$
Energy	ρ	0	h	h	h	T	k	$q_e\left[b\left(E_x^2+E_y^2\right)+uE_x+vE_y\right]$ $-D_e\left(E_x\frac{\partial q_e}{\partial x}+E_y\frac{\partial q_e}{\partial y}\right)$
Electric potential	0	0	0	0	0	φ	-1	$\frac{q_e}{\varepsilon_0}$
Electric charged particle transport	1	b	q_e	q_e	q_e	q_e	D_e	0

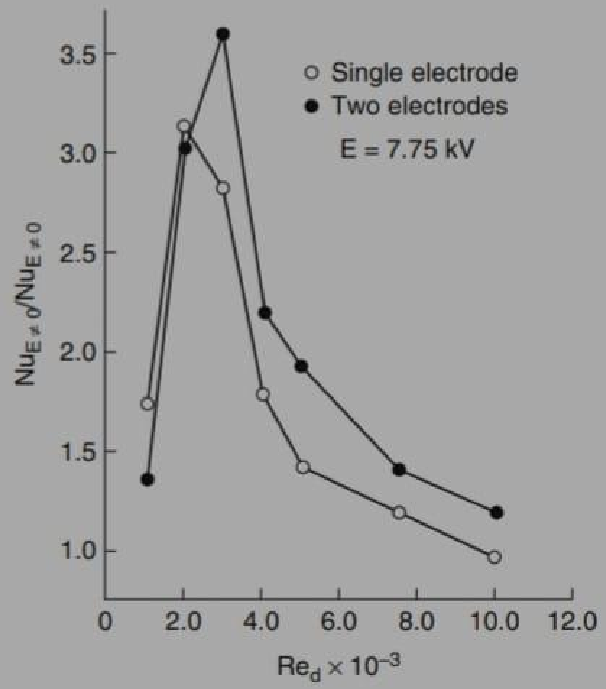
9. Enhancement of Gas Flow

Electrophoretic force may cause EHD induced fluid motion known as ionic (or Corona)wind effect for single phase flow. Ions are produced close to the surface of a word anode. The coulomb Force on the ions is responsible for the ions to move to the cathode surface. Interaction of the Corona wind with main flow produces mixing by secondary flow, the greatest enhancement occurs for low Reynolds number laminar natural convection increase in the main flow velocity, and the secondary flow speed is insignificant in comparison with strength of the turbulent eddies. The figure below shows the first convection enhancement data observed by Ohadi et al.(1991a). The used single and double axial electrodes to measure the enhancement of air flow. Ohadi et al.(1991b)used axial wire electrodes in a double pipe heat exchanger with air flow in both streams. EHD

enhancement data were given by them for tube- side, shell -side and both fluids. Ohadi et al. (1991b) used extend the work to a shell and tube heat exchanger consisting of 7 tubes. 1000 <Re<6000 was used for the tube and the shell side. More than 100% enhancement was obtained at the lowest Reynolds number when both sides were excited. With the increase of Reynolds number however, the enhancement decreased. Nelson et al. Studied EHD enhancement of the air flow in a circular tube using a central axial electrode . They observed almost similar increase in pressure drop and the heat transfer . Blanford et al. 1995 applied EHD technique to enhance air- side heat transfer of a one row finned tube

heat exchanger. Kasayapanand et al. 2006 studied electrodynamic technique for heat transfer in a solar air heater with double flow configuration. Laminar forced convection was considered for study .Solar air heater double flow configuration has been shown in the figure below .Five different types of arrangements of electrodes have been presented .They observed Rotating cellular motion around the all electrodes .But as the number of the electrode is high in compared to that case1 more vortices more around the electrode were observed. Also oscillating flow patterns were reported because high density of electric field.

Fig. 2.6 Enhancement provided by axial single- and double-wire electrodes in a 38.4-mm-diameter tube from Ohadi et al. (1991b)



10. Enhancement of Liquid Flow

Fernandez and Poulter (1987) worked with Transformer oil flowing side of annulus of a double -pipe heat exchanger . Mirzaei and Saffar-Avval with novel double pipe heat exchanger with the outer Pipe having teflon parts and copper inner pipe. Their objective was to configure the electrodes for heat transfer enhancement in annuli and its mounting. The electrode configuration has been presented with their dimensions in the table. They made the following assumptions:

1. For symmetric electrodes the net flow generation of EHD conduction from depends on the charge mobility and if the movie negative charge is higher than that of the positive charge it would be from the cathode to anode and;

2. The net flow generation for the identical negative and positive charge mobility would be from narrower electrodes to wider electrodes. They used transformer oil as the working fluid and the pumps and testing section including double pipes .The testing section has six EHD pumps and each pump consists of PTFE electrode holder. The fluid motion and electric field are governed by Navier-Stokes equations and Maxwell's

equations respectively. They considered steady state incompressible fluid with no charge injection from electrodes. They used final volume methods and algorithms for equation solving and pressure velocity coupling respectively. EHD heat transfer enhancement increases by 50% and 21% at Reynolds number 10 and 30 respectively. The enhancement is effective at the lower Reynolds number. Concluded that

pressure drop decreased with increase in Reynolds number as well as list for 8 kv than that for 16 KV. The Nusselt number variation with pumping power and effectiveness parametre versus Reynolds number. They observed that the electric field enhances in transfer. The increase in voltage electric force caused in formation of two vortices which became prominent with increase voltage.This is reason behind the heat transfer

enhancement.

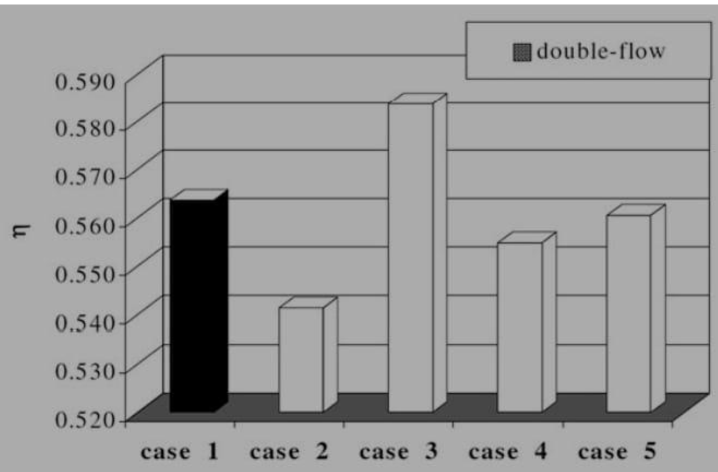


Fig. 2.9 Efficiency of the solar collector with double flow (Kasayapanand et al. 2006)

11. Condensation

11.1 Vapor Space Condensation

Wawzyniak and Seyed-Yagoobi conducted EHD-enhanced R-113 condensaion tests on a vertical enhanced tube (Turbo-CH, shown in Figure 12.6) and on a smooth tube. The Figure 15.3d helical wire electrode was placed with a 1.6-mm gap from the tube. The heat transfer enhancement by EHD was larger for the enhanced 1.lbe-approximately 100% for the Turbo-CH and less than 100% for the smooth tube. The reason was attributed to the non-uniform electric fields caused by the fins of the enhanced tube. Cheung et al. investigated the effect of electrode-tube gap width of the Figure 15.3d electrode using R-134a on smooth tubes. Both vertical and horizontal configurations were studied. The gap width was varied from 0.8 to .2 mm. For both configurations, the largest (3.2 mm) gap yielded the highest heat transfer enhancement and with the least amount of electrical power to the electrode.

Da Silva et al.investigated the effect of polarity on the EHD enhanced condensation of R- l 34a on horizontal enhanced tubes. The Figure 15 .3d helical wire electrode was placed with 3.0-mm gap from the tube. An enhancement ratio of 3.5 was obtained when a positive polarity field was applied compared with 1.5 for the negative polarity case. The condensate extraction from the tube, which was seen clearly for the positive polarity case, was not readily observed for the negative polarity case. Chu et al. investigated the film condensation enhancement of steam on a 16-mm-OD, LO-mm-pitch integral fin tube . A 1.0-mmdiameter stainless wire electrode was placed under the finned tube parallel to the tube axis. The figure shows that the enhancement ratio jumps to a higher value above a threshold voltage. The threshold voltage is higher for larger H. The maximum enhancement ratio of 2.5 was obtained. Fi shows the measured flooding angles and Figure 15.11 shows corresponding flow patterns for H = 1.0 mm. For zero voltage, the tube and the wire electrode are bridged by the condensate film, and the interfin spaces are completely flooded (90° flooding angle). When the applied voltage is above the threshold value (765 V), the bridging film becomes liquid columns, and the flooding angle decreases to 45°. With further increase of the voltage, the pitch of the liquid columns decreases, and the flooding angle decreases yielding higher enhancement ratio. Chu et al. also provides an analytic model that predicts the EHD condensation on integral-fin tubes.

11.2 In-Tube Condensation

The EHD technique was applied to in-tube condensation by Singh et al.and Gidwani et al, Singh et al. investigated EHD enhancement of R- l34a condensation in a 12.7-mm-OD smooth tube and in a microfin tube of the same outside diameter for mass flux from 50 to 300 kg/m--s. Six different electrodes 1aving various electrode diameters and spacings were tested. The optimum electrode (maximum heat transfer enhancement) was the one placed coaxially with a sufficiently large electrode gap. For the smooth tube, up to 6.4-fold heat transfer enhancement was obtained at the lowest mass flux and quality investigated. The enhancement decreased as the mass flux and the quality increased. The pressure drop increase was more pronounced than the heat transfer increase. For the rnicrofin tube, the heat transfer enhancement was much less than that of the smooth tube. A maximum value of 1.8 was obtained. They state that the electric field strength is high at the tip of the microfin, and the condensate is not easily pulled to the electrode as occurs in the smooth tube. For the smooth tube, the electric potential is the highest at the electrode, which pulls the condensate to the electrode, leaving thin condensate film at the tube wall. Gidwani et al. extended the study to a corrugated tube. Similar to the microfin tube, the enhancement ratio of the corrugated tube was less than that of the smooth tube.

11.3 Falling Film Evaporation

Yamashita and Yabe applied the EHD technique to enhance R-123 falling film evaporation from a vertical smooth tube. In addition to the conventional electrode geometries shown in Figure 15.4, punched electrodes shown in Figure 15.12 were tested. The electrodes were made from rolled plates with punched slits of 2.0 mm width and 30 mm length. Electrode III has slit configuration similar to Electrode I, except that the slits are arranged offset in the vertical direction. The gap between the tube and the electrode was 3.05 mm. Generally, the punched electrodes yielded higher enhancements than conventional electrodes. Different from the condensation case, there existed an optimum applied voltage, at which the heat transfer coefficients were maximized. They state that above the optimum value, EHD causes dryout of the film. compares the measured optimum Nusselt number vs film Reynolds numbers for the three punched electrodes. Data were taken at q=10,000 W/m2.

Darabi et al. investigated the effect of EHD on falling film evaporation of vertical enhanced tubes (748 fpm integral fin tube and Turbo-BIII) using R-134a. Turbo-BIII is shown in Figure ll.12e. A punched electrode was used for Turbo-BIII and a wire electrode wrapped with nylon strand was used for the integral fin tube. Up to 80% enhancement was obtained for the smooth tube, 110% for Turbo-BIII, and 30% for the integral fin tube. The enhancement decreased with increasing heat flux. Darabi et al. extended the study to the horizontal configuration. Tested tubes included: smooth, 748-fpm integral-fin, Turbo-BIII. Enhancement up to 280% was obtained with the smooth tube, 90% with the Turbo-BIII tube, and 60% with the integral-fin tube.

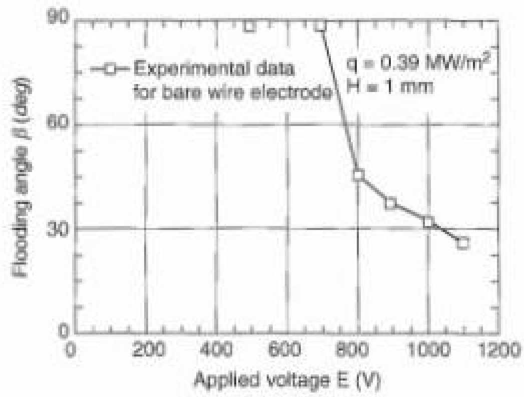


Figure 15.10 Condensate flooding angle vs. applied voltage for condensing steam on 16-mm-OD, 1.0-mm integral-fin tube. A 1.0-mm-diameter stainless wire electrode placed under the tube at a distance $H = 1$ mm. (From Chu et al. [2001].)

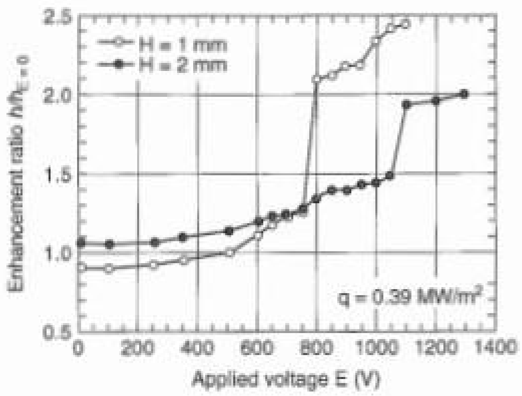


Figure 15.9 Heat transfer enhancement ratio vs. applied voltage for condensing steam on 16-mm-OD, 1.0-mm integral-fin tube. A 1.0-mm-diameter stainless wire electrode placed under the tube at a distance H = 1 and 2 mm. (From Chu et al. [2001].)

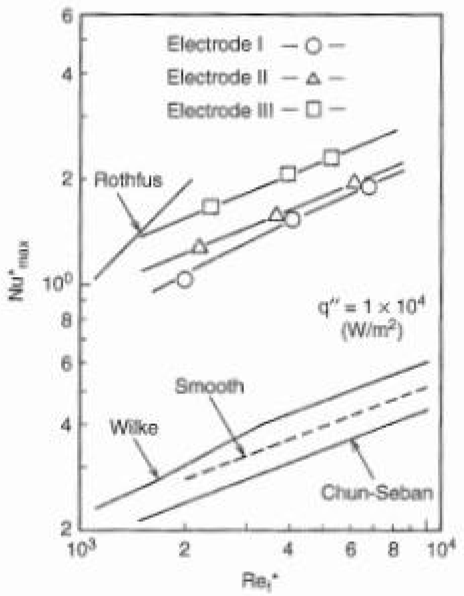


Figure 15.13 Optimum Nusselt number vs. film Reynolds number, obtained with punched electrodes of Figure 15.12. (From Yamashita and Yabe [1997]. Reprinted with permission of ASME.)

12. Boiling

12.1 Pool Boiling

Papar et al. investigated the effect of electrode geometry on EHD enhanced boiling of R-123/oil mixtures on a horizontal smooth tube. The electrode geometry included wire mesh, straight wire, and helical wire (Figure 15.3 a, b, and d). The mesh electrode performed better than the other geometries yielding up to a fivefold enhancement. The oil degraded the enhancement and increased the electric power consumption. Singh et al. extended the study to 748 and 1575 fpm integral fin tubes. An 11.5-fold enhancement was obtained for the 1575 fpm integral fin tube when a mesh electrode was used. Yan et al. investigated the EHD effect on the pool boiling of high-performance boiling tubes

Thermoexel-HE and GEWA-T (surface geometry shown in Figure 11.12). A mesh electrode was used to enhance R-114 boiling. Approximately 75% enhancement was obtained for the Thermoexel-HE. The enhancement was much smaller for GEWA-T. The boiling hysteresis was completely eliminated with the application of electric field. Darabi et al. provide additional data on R-134a boiling of integral-fin tubes and Turbo-BUI.

Zaghdoudi and Lallemand investigated the effect of electric field polarity on nucleate pool boiling of n-pentane on a horizontal plate. The negative polarity configuration yielded a larger enhancement than the positive polarity configuration. They state that, for the positive polarity, the dielectrophoretic force (second term in Equation 15 .1) is directed from the heated surface to the liquid. For the negative polarity, the dielectrophoretic force is directed from the liquid to the surface. The electrostriction force (third term in Equation 15 .1) always acts to the surface independent of the polarity. Thus, stronger wall-bound electric force is manifested for the negative polarity compared with the positive polarity.

12.2 Convective Vaporization

Yabe et al. studied convective vaporization of R-123 and R-134a inside a circular tube. A three-factor enhancement was obtained at 33 kg/m2-s over a wide range of vapor qualities. The enhancement ratio decreased as the mass flux increased. More dramatic enhancement is obtained in nucleate pool boiling. Singh et al. provide additional data on EHD enhancement of R-123 and R-134a in a circular tube. A similar level of enhancement to that measured by Yabe et al. was obtained. Bryan and Seyed-Yagoobi conducted R-134a boiling in a smooth tube. Interestingly, they noticed that, at high vapor qualities, the heat transfer coefficient was reduced with application of EHD. This phenomenon was more prominent at low mass fluxes and high heat fluxes. The electric force, which thins the liquid film by extracting the liquid from the wall, was suspected to cause an eary dryout. The reduction of heat transfer coefficient at high qualities by EHD was also reported by Norris et al.

. Ogata et al. tested R-123 boiling on a horizontal bundle of 50 plain tubes using six axial wire electrodes spaced at 3.0 mm from each tube. They show that the performance of the tube bundle is competitive with that of a single tube. An economic analysis of EHD enhancement is also provided. Cheung et al conducted EHD enhanced boiling of R-134a in a bundle of seven integral fin tubes having 1575 fpm. Six straight wire electrodes were spaced at 3.5 mm from each tube. A threefold increase in the overall heat transfer coefficient was obtained at 5 kW/m2. The enhancement decreased as the heat flux increased. When a circular mesh electrode (Figure 15.3c) was used, the enhancement increased to fivefold. Karayiannis investigated the EHD effect for R-123 and R-11 boiling on a horizontal tube bundle of five tubes. Fourteen straight electrodes were placed around the tubes. A 9.3-fold enhancement was obtained for R-123 at 5 kW/m2. The enhancement decreased significantly as the heat flux increased. The enhancement with R-11 was only marginal. Karayiannis attributed the reason to the longer electric relaxation time of R-11 than the bubble detachment period. If the relaxation time is long, the electric forces generated on the bubbles are too weak to affect the bubble behavior significantly.

12.3 Critical Heat Flux

Zaghdoudi and Lallem and investigated the effect of EHD on CHF from a horizontal plate. For n-pentane and R-113, the increase in CHF with the electric field was 17 and 23%, respectively. For R-123, however, a threefold increase was obtained. They state that the electric field has an effect of decreasing the most critical wave length (refer to Equation 11.35), which leads to an increase of CHF. Yabe reported the 20% increase of CHF of R-113 when a uniform electric field of 20 kV /cm is applied.

13. Conclusion

In this report we have covered the basics of an introduction to enhancement of heat transfer using electric field. We have reviewed literature regarding this subject. We have covered design and placement of electrodes and reviewed their industrial importance. Next we have discussed enhancement of gas and liquid flow .Then we have covered the understandings of condensation and boiling.

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