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ELECTROHYDRODYNAMIC (EHD) ENHANCEMENT OF TWO-PHASE HEAT TRANSFER

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ABSTRACT

This paper describes recent research into enhancement of condensation and boiling heat transfer through the use of intense electric fields: i.e. Electrohydrodynamic (EHD) enhancment. Results of research in the UK for EHD augmented condensation for refrigerant 114 on a single tube are presented. This is contrasted with results from Japan for a demonstration 50kW EHD condenser.

Recent advances in EHD enhancement boiling are also presented. Research by the present author has shown that by combining a practically realisable electrode configuration with a favourable heat transfer surface geometry, nucleate boiling heat transfer coefficients may be increased by up to an order of magnitude. A theoretical model of EHD nucleate boiling in simple geometries is described where a non-dimensional electrical influence number, Ne, based on bubble departure diameter, is used to correlate EHD nucleate boiling data from previous experiments by others on fine heated horizontal wires.

INTRODUCTION

The phenomenon of electrohydrodynamic (EHD) enhancement of heat transfer was first reported some seventy years ago (Chubb, 1916). Since that time considerable fundamental research has been carried out in this field and a comprehensive review of the literature was made by Jones (1978). It is the aim of this paper to detail some of the most recent experimental and theoretical advances.

EHD enhancement of heat transfer involves the application of an intense electric field, $\mathbf{E}$, to a convective heat transfer surface. The presence of this field in the heat transfer medium, together with thermal and electrical inhomogeneities, gives rise to body forces within the fluid of electrical origin. The resultant electrical body force, $\mathbf{F_e}$, has been shown to be (Stratton, 1941):

$$\mathbf{F_e} = \rho_f \mathbf{E} - \frac{E^2}{2}\nabla\varepsilon + \frac{\rho}{2}E^2\left(\frac{\partial\varepsilon}{\partial\rho}\right)_T \qquad (1)$$

where ε, ρ and ρ_f are dielectric permittivity, density and free electric charge density of the fluid, respectively. The first term on the right hand side of (1) represents the "electrophoretic" forces on fluid free charges; the second term represents forces due to changes in the fluid permittivity and the remaining term contains contributions from both "dielectrophoretic" forces and "electrostriction". In two-phase EHD heat transfer it is generally held that the second and third terms on the right side of (1) are most important in fluids with low electrical conductivity. On the other hand, many single-phase situations (where free-charge density may be significant) are characterised by electrophoretic EHD phenomena. Allen (1988) has recently summarized much previous work on dielectrophoretic heat transfer enhancement.

To maintain an intense electric field continuously in a heat transfer medium, the fluid must be a dielectric (i.e. electrically insulating). Practical examples of such fluids include mineral oils and Freons. In two-phase heat transfer the electric forces are manifest: i) within each phase (e.g. causing enhanced convection within the liquid phase) and ii) as a result of the distinct electrical permittivities of the two-phases. An example of the latter is where bubble dynamics in EHD nucleate boiling are considerably modified by the presence of an electric field. In both cases i) or ii) above, dielectrophoretic forces tend to move matter of higher permittivity towards regions of higher electric field strength.

Practical implementation of EHD techniques requires the addition of electrodes and a high voltage source to the normal heat exchanger. Thus, large heat exchangers, condensers and evaporators would appear to provide the most cost-effective applications. Much of the earlier fundamental EHD research was carried out on apparatus with thermal and electrical geometries inappropriate to practical situations. The aim of the research described below, in both the UK and Japan, has been the realization of an effective practical electrode system for incorporation into shell-tube heat exchangers (though the approaches adopted differ considerably).

EHD ENHANCEMENT OF CONDENSATION HEAT TRANSFER

Investigation of EHD enhancement of condensation heat transfer was first reported in the 1960's and indicated that substantial enhancement was possible for many electrical and thermal geometries in laboratory apparatus. In the case of condensation heat transfer two basic types of EHD enhancement mechanism have been observed, both effectively thin the condensate film (which represents the major thermal resistance to heat flow):

A) EHD condensate film wave instability. Electric forces present at the vapour/liquid interface lead to a wave-like instability on the surface of the condensate film . Since heat flux is inversely proportional to local film thickness (to a first approximation), the mean heat flux over the heat transfer surface is increased.

B) "EHD pumping" (or condensate film "stripping"). This occurs in intense or highly non-uniform fields. The condensate film is completely disrupted and thinned by actual loss of liquid electrically pumped to a region of high field intensity (e.g. at a small diameter electrode).

The design of electrode systems for incorporation in commercial heat exchangers must take account of both: a) the mode of EHD enhancement employed and also; b) the practical aspects of insulation and support of the electrode system from the rest of the heat exchanger. Allen and the present author developed an electrode system comprising a combination of high voltage plates and rods placed between the tubes of a shell-tube heat exchanger as shown in Fig. 1 (Allen and Cooper, 1985).

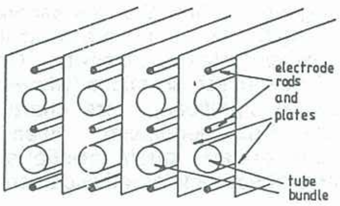

Figure 1. Plate and rod EHD electrode system for a tube bundle (UK).

This system may be used for enhancement of single or two-phase heat transfer on the outside of a tube bundle in horizontal or vertical orientations and is optimized with respect to maximization of the strength and uniformity of the electric field around tube circumference. When applied to a condenser it is then possible to utilize both the EHD wave instability mechanism (A) at modest electrode voltages and EHD pumping (B) at high voltages (particularly with thick films on a vertical tube). A single-tube version of an EHD condenser (modelling a tube in the top row of a tube bundle) was tested in a simple Freon boiler/condenser loop with R114 and R12 used as heat transfer media (Cooper, 1986). A typical set of test results is shown in Fig. 2. Enhancement of mean condensation heat transfer coefficients by up to a factor of three was achieved (the maximum enhancement being limited by the inadequacies of the particular electrode insulation system employed rather than by hydrodynamic factors). This research programme continues at the City University (UK) with tests underway on a nine-tube EHD evaporator and condenser designed by the present author (Cooper, 1986).

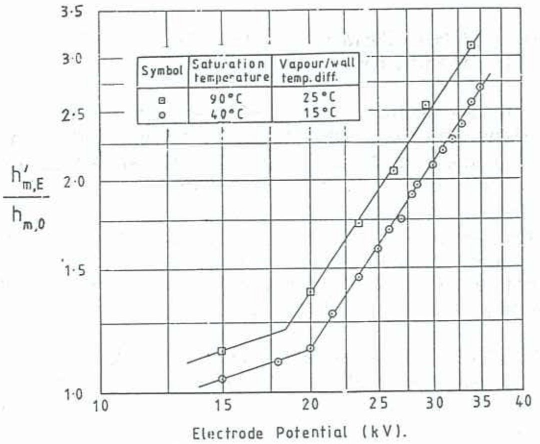

Figure 2. Enhancement of condensation heat transfer of R114 on a vertical tube

Researchers in Japan have also taken important steps toward the development of a commercial EHD condenser system. The approach there has been to adopt an electrode system that utilizes EHD pumping as the primary enhancement mechanism. Two electrode systems tested are shown in Fig. 3. This type of system can only be applied to tubes in the vertical orientation. Laboratory tests have indicated that enhancement ratios of up to four times may be achieved. A demonstration plant under the auspices of the Super Heat Pump Energy Accumulation System (NEDO, 1988) has been recently commissioned and includes a 50 kW vertical EHD condenser with 36 tubes. Performance is reported to be comparable with that of the single-tube laboratory rig (see Fig. 4).

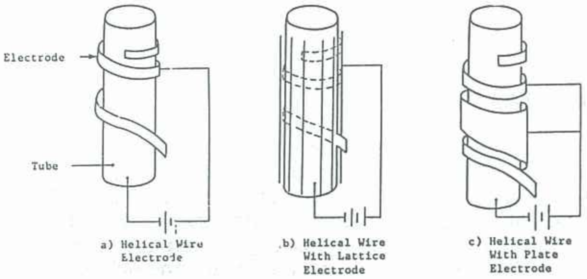

Figure 3. Three EHD electrode arrangements for enhancement of condensation (Japan)

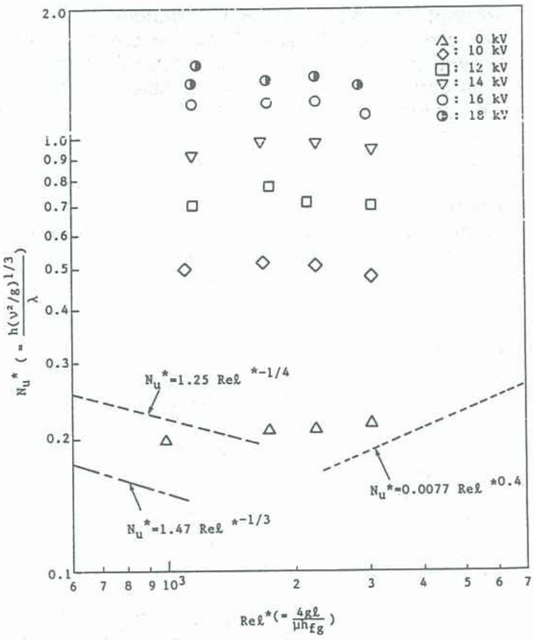

Figure 4. EHD enhancement of condensation in a 36 tube vertical 50kW R114 condenser (Japan)

EHD ENHANCEMENT OF NUCLEATE BOILING HEAT TRANSFER

The earliest work on EHD heat transfer was concerned with boiling in water (Chubb, 1916). However, more than four decades were to pass before a quantitative study of EHD enhanced boiling was carried out (by Bochirol et al, 1960). The majority of research that followed was concerned with the film boiling region where application of an intense electric field was found to disrupt the vapour film (in a manner similar to the EHD condensation wave instability) and produce very significant increases in heat transfer coefficient. Enhancement of nucleate boiling in simple thermal and electrical geometries was observed to be relatively small and some researchers have reported that application of an electric field actually causes an inhibition of boiling.

Through experimental research in the UK using the electrode geometry of Fig. 1 and R114 as the heat transfer fluid, the present author has demonstrated that: i) Application of a continuous intense electric field to a horizontal tube with integral fins (a "lo-fin" tube) can result in EHD enhancement of boiling heat transfer coefficients by up to an order of magnitude; and has confirmed the earlier work of others that: ii) Application of a brief electric field (< 1sec) of moderate intensity eliminates boiling hysteresis.

A summary of some experimental results for a single horizontal lo-fin tube is shown in Fig. 5 (see Cooper, 1986, for further detail). Recent EHD boiling research in Japan is less developed than the EHD condensation program, however a 50-tube EHD evaporator has been commissioned and tested (Kawahira et al, 1987).

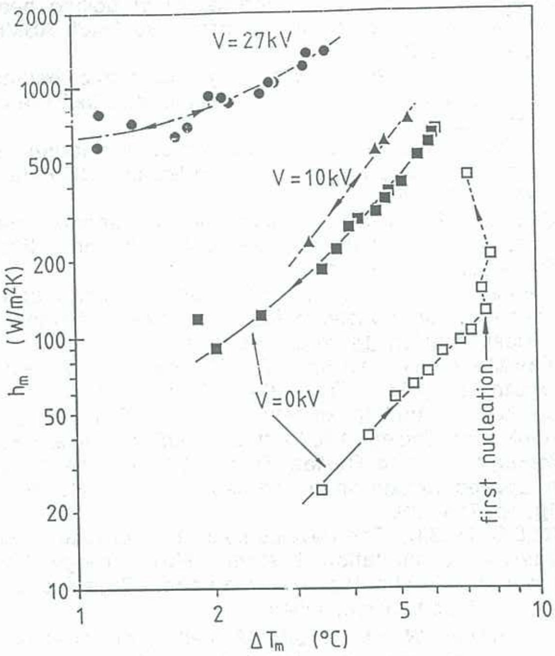

Figure 5. EHD enhanced boiling heat transfer coefficient, h_m, on the outside of a horizontal "lo-fin" tube in R114 (saturation temp. = 21.5°C) as a function of tube-to-fluid superheat, ΔT_m.

CORRELATION OF EHD NUCLEATE BOILING EXPERIMENTAL DATA

EHD enhanced boiling heat transfer is an extremely complex process since the governing equations for the hydrodynamic, thermal and electrical fields are all coupled. Until recently, theoretical treatments of EHD boiling have been concerned only with the film boiling regime and prediction of the increase in critical heat flux through application of an electric field. Recent research in Japan and the UK has resulted in two quite different approaches to the modelling of EHD nucleate boiling data. Yokoyama et al (1986) investigated a horizontal upward facing flat heated plate in an EHD pool boiling situation (working fluid R11) and developed a method of correlating the experimental results based on the analysis of zero-field flow boiling heat transfer by Chen (1963).

The present author has developed a means of correlating EHD nucleate boiling data for simple geometries, principally those using a cylindrical, small diameter heat transfer surface. It is assumed that the influence of the electric field on bubble growth and separation at the heat transfer surface is the primary cause of EHD induced changes in nucleate boiling heat transfer coefficient. The basis of the approach is the zero-field model of nucleate boiling proposed by Rosenhow (1952) which is modified to account for the observed reduction in bubble release radius in an electric field. The Rosenhow model utilizes bubble release radius as a characteristic dimension in both the Nusselt number, Nu_0, and the Reynolds number, Re_0 (the subscripts $_0$ and $_E$ refer to the zero and finite applied electric fields, respectively). The following equation was proposed as a means of correlating nucleate boiling data:

$$Nu_0 = C_1 . Re_0^{(1-n)} . Pr^{(-m)} \tag{2}$$

From various data of boiling on clean surfaces Rosenhow suggested values of n=0.332, m=0.7 and C_1 is a constant dependent on the fluid/heating surface pair.

Research in the Soviet Union by Baboi et al (1968) investigated the phenomenon of bubble departure diameter, D_b, reduction as a function of applied electric field intensity in EHD pool boiling of benzene on a fine horizontal heated wire. The electric force, F_E, acting on a bubble (assuming uncharged bubbles) was calculated as:

$$F_E = \left(\frac{1.5\, \Gamma_b\, \varepsilon_L (\varepsilon_V - \varepsilon_L)}{(\varepsilon_V + 2\varepsilon_L)} \right) \nabla E^2 \tag{3}$$

where Γ_b is the volume of a bubble ε is absolute permittivity (subscripts V and L denote vapour and liquid, respectively) and E is electric field strength at the heat transfer surface. By considering a steady-state balance between electric, buoyancy and surface tension forces Baboi et al determined bubble breakaway diameter to be:

$$D_b = w(\beta) \left(\frac{\sigma}{g(\rho_L - \rho_V)} \right)^{0.5} \tag{4}$$

$$\times \left(1 + \left(\frac{1.5\, \varepsilon_L (\varepsilon_V - \varepsilon_L)}{(\varepsilon_V + 2\varepsilon_L)\, g(\rho_L - \rho_V)} \right) \nabla E^2 \right)^{-0.5}$$

where w is a function of contact angle, β. The change in D_b can be seen as an electrically induced change in the characteristic dimension of Nu_0 and Re_0. Thus, equation (3) may be used to determine the magnitude of electrically modified Reynolds and Nusselt numbers, Re_E and Nu_E, respectively. Defining an electrical influence number, Ne:

$$Ne = \left(1 + \left(\frac{1.5\, \varepsilon_L (\varepsilon_V - \varepsilon_L)}{(\varepsilon_V + 2\varepsilon_L)\, g(\rho_L - \rho_V)} \right) \nabla E^2 \right)^{-0.5} \tag{5}$$

then

$$Nu_E = \left(\frac{h_E}{h_0} \right) Nu_0\, (Ne)^{-0.5} \tag{6}$$

and

$$Re_E = Re_0\, (Ne)^{-0.5} \tag{7}$$

Thus, for constant heat flux and saturation temperature, combining (2), (5), (6) and (7) the degree of EHD enhancement of heat transfer is given by:

$$\left(\frac{h_E}{h_0} \right) = Ne^{(n/2)} \tag{8}$$

A number of simplifying assumptions are made in the foregoing analysis; the most limiting being the steady state derivation of Ne and, therefore, that Ne is independent of heat flux. Experimental data from all sources shows that Ne decreases with increasing heat flux and the present author has therefore proposed the following model which includes the influence of zero-field dimensionless heat flux, Re_0:

$$\left(\frac{h_E}{h_0}\right) = a\,Ne^{(n/2)}\,(Re_0)^b \qquad (9)$$

where n=0.33 as suggested by Rosenhow and where a=0.3 and b=-0.16 have been determined empirically by the present author from studies by others of EHD nucleate saturated pool boiling on fine horizontal wires. Data used for determination of these coefficients were taken from: Baboi et al (1968); Choi (1962); Bonjour et al (1962). The correlation of these data together with two other studies by Watson (1961) and Markels et al (1964) are shown in Fig. 6. [Note: experiments by Watson included a substantial degree of subcooling and those of Markels et al involved a significant degree of joule heating of the working fluid, water, and these data have not been used to determine constants a and b]

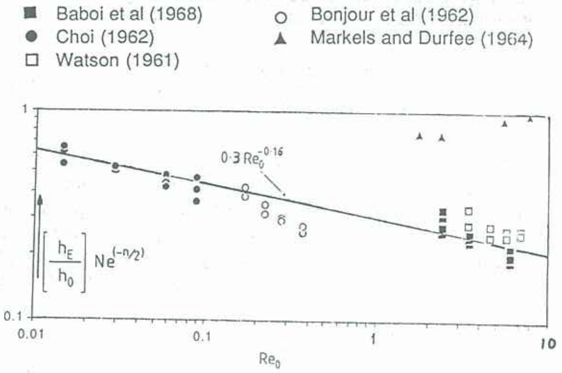

Figure 6. Correlation of EHD boiling data for fine heated wires using equation (9)

DISCUSSION

After many years of fundamental research, EHD two-phase heat transfer enhancement development is nearing engineering potential for commercial applications. Research in the UK and Japan has demonstrated that EHD electrode systems can be fabricated on a demonstration scale and can be incorporated into shell-tube heat exchangers using Freons as the heat transfer medium. The major conclusions from this work may be summarized as follows:

i) EHD enhancement of condensing heat transfer by a factor of three or more may be achieved in large condensers.
ii) Boiling hysteresis may be eliminated by electrical activation of boiling using the brief application of a modest electric field.
iii) Enhancement of nucleate boiling heat transfer by up to an order of magnitude may be achieved (on a laboratory scale) through the use of suitable thermal and electrical geometries.

Equation (9) successfully models EHD nucleate boiling from heated horizontal wires where conventional nucleate boiling bubble dynamics occur. It does not, however, model more complex EHD heat transfer situations.

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