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The mechanisms of heat transfer during convective boiling under the influence of AC electric fields

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ABSTRACT

In this investigation the local heat transfer coefficients along the top and bottom of a horizontal tube heat exchanger within which convective boiling of HFE7000 is occurring are measured. Of particular focus is the influence of Electrohydrodynamics (EHD) on the flow regimes and associated heat transfer. To achieve this, thermocouples are embedded into the walls of a transparent sapphire tube coated with a transparent yet electrically conductive layer of Indium Tin Oxide (ITO). The ITO layer allows visual access to the two phase flow while at the same time acts as an electrical heater element for the heat transfer and electrical ground for establishing the electric field. Tests have been performed for a fixed mass flux of $G = 100\ \text{kg/m}^2\ \text{s}$, inlet quality of $x = 3\%$ and applied heat flux of $q'' = 12.4\ \text{kW/m}^2$. An AC 60 Hz high voltage was applied across the fluid up to 8 kV in increments of 1 kV. The results show that, for the conditions tested, the application of EHD substantially increases the heat transfer coefficient at all measurement locations on the heat exchanger. Near the entrance, the top surface heat transfer enhancement reached over 7.2-fold and this decreased monotonically to 2.4-fold at the exit region. The bottom enhancement was more uniform along the heat exchanger ranging between approximately 3 and 4-fold at the highest applied voltage tested. The mechanisms responsible for the observed enhancement levels are discussed in the context of the flow regimes observed using high speed videography.

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1. Introduction

Heat exchangers that utilize phase change are used extensively since they offer several advantages over single phase systems. These include, though are not limited to, higher achievable heat transfer coefficients, lower liquid content and temperature uniformity. Like their single phase counterparts, much research has been performed to enhance the performance of two phase heat exchangers. This includes techniques to redistribute the phases causing enhanced mixing and wetting, techniques to increase the internal surface area as well as techniques to cause flow regime transitions to those which are more favorable for heat transfer.

Electrohydrodynamics (EHD) is the branch of thermal fluid science that deals with the interaction of electric fields with fluids. In two phase systems, it is known that EHD can augment the flow field in such a way as to realize significant enhancement in the heat transfer [1–3]. Although significant progress has been made, the precise mechanisms of flow and heat transfer augmentation are still not well understood.

Panofsky and Phillips [4] among others, forwarded the following expression for the forces induced on a dielectric medium within an electric field;

$$f_e = \rho_e \overline{E} - \frac{1}{2}E^2\nabla\varepsilon + \frac{1}{2}\nabla\left[\rho E^2\left(\frac{\delta\varepsilon}{\delta\rho}\right)_T\right] \tag{1}$$

The three terms in Eq. (1) represent the electrophoretic, dielectrophoretic, and electrostrictive components of the EHD force respectively. The electrophoretic force is that which acts on the net free charge within the fluid and is the only force that is dependent on the polarity of the electric field. The dielectrophoretic force arises due to spatial gradients of the permittivity. Interestingly, in a two phase flow the difference in permittivity of the two phases at the extremely thin liquid–vapor interface may cause this force to be significant. It is known to cause liquid extraction which is thought to be a key mechanism for redistribution of the phases resulting in heat transfer enhancement [5]. The last term is the electrostrictive force which arises due to inhomogeneity of the permittivity with density at constant temperature.

Over the past two decades there have been many studies on the topic of EHD augmentation of two phase flow and heat transfer. Adequate summaries can be found in the reviews by Jones [6], Allen and Karayiannis [7], Seyed-Yagoobi and Bryan [8] and

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Nomenclature

A	surface area
A_i	cross sectional area
$C_{p,r}$	refrigerant specific heat
d_i	test section inner diameter
D_h	hydraulic diameter
E	electric field strength
f_e	electric body force
G	mass flux
h_{fg}	latent heat
I	current
h	heat transfer coefficient
L	length
$\dot{m}$	mass flow rate
P	pressure
Q_{DIR}	heating in DIR1
Q_{HEX1}	heating in HEX1
q''	heat flux
q	heat transfer rate
q_{total}	total heat transfer rate
$q_{natconv}$	natural convection losses
T	temperature
T_{sat}	saturation temperature
T_{wall}	tube wall temperature
ΔT_{sup}	wall superheat
V	voltage
w_i	uncertainty in measurement
w_z	uncertainty in calculated result
x_i	measurement
Z	calculated variable
x	working fluid inlet quality
z	length along test section

Greek symbols

ε	dielectric permittivity
μ_c	ion mobility
μ_L	dynamic viscosity
ν	kinematic viscosity
ρ	density
ρ_e	charge density

Laohalertdecha et al. [3]. The preponderance of the research involved the influence of DC electric fields on the flow and heat transfer for both flow boiling and condensation [9–17]. In general, the studies show that EHD can enhance the heat transfer from anywhere between 1.6 and 5.5-fold and the level of enhancement depends on the specificities of the experimental apparatus utilized i.e. working fluid, test section geometry, electrode configuration, etc. Even still it should be cautioned that this is not always the case as there are instances where EHD can cause premature dryout with associated deterioration in the heat transfer [13].

More recently the influence of AC EHD on two phase flow and heat transfer has been studied [2,18,19]. In Ref. [2], both moderate (60 Hz) and high (6.6 kHz) frequencies were investigated for convective boiling of R134a along with DC applied voltages. The work showed that the high frequency behavior was the same as that for DC. However, the moderate frequency resulted in the highest heat transfer. Due to the test section being metallic, the flow regimes could only be inferred from wall superheat measurements and thus the mechanisms of heat transfer were not clearly understood although the net effect could be quantified. The recent work of McGranaghan and Robinson [1] did provide a partial solution to this shortcoming of earlier investigations which used fluid–fluid heat exchangers by using sapphire tubing coated with Indium Tin Oxide (ITO). The advantage of this heat exchanger test section is that the sapphire is transparent and thermally conductive whilst the ITO coating provided electrical ground for establishing the electric fields. Thus, the flow regimes could be visualized using high speed videography and used to help explain the observed heat transfer behavior. Even still, this work only investigated the average heat transfer of the fluid–fluid heat exchanger with a uniform wall superheat as the test section configuration and measurement technique utilized was not amenable to local heat transfer measurements.

The objective of this investigation is to contribute to knowledge in the field of EHD augmented two phase flow and heat transfer by providing local heat transfer measurements along the length of a test heat exchanger which is subject to high intensity AC electric fields. An added novelty is the use of the ITO coated sapphire which ostensibly results in a transparent, thermally and electrically conductive heat exchanger which facilitates visualization of the flow patterns *in situ*. The observed local flow patterns and the flow pattern development are then used to help understand the augmentation of the local heat transfer rates as well as the profiles of the heat transfer coefficients.

2. Experimental apparatus

A schematic of the test facility is illustrated in Fig. 1. It consists of a primary closed circuit charged with the refrigerant HFE7000 as the working fluid. A gear pump circulates the refrigerant through a pre-heating section, the test section and a condenser. The pre-heating section consists of two heat exchangers. The first is a direct contact electrical heater (DIR1) and the second is a compact plate heat exchanger (HEX1), which uses hot water from the first secondary loop (SEC1) to heat the refrigerant. Knowledge of the thermodynamic state of the refrigerant entering DIR1 along with careful monitoring and control of these preheating stages allows the determination of the thermodynamic state of the refrigerant entering the test section, in particular the inlet quality. The refrigerant passes through an adiabatic length of flexible piping and a straight developing length before entering the test section, which is a horizontal electrically heated tubular heat exchanger. On exiting the test section, the refrigerant is condensed by an additional compact heat exchanger (HEX2) supplied by cold water from a temperature controlled chiller unit. Various ancillary valves on the loop allow for pressure control, removal of non-condensable gas, charging and drainage.

The test section depicted in Fig. 2 is novel in that it is optically transparent allowing visualization of the refrigerant fluid flow regime under both EHD and non-EHD conditions. The test section is a 480 mm long sapphire tube of 10 mm outside diameter and 8 mm inside diameter supported in two machined polypropylene supports which connect it to the other pipe work. A circular stainless steel rod of 3 mm diameter runs concentrically along the inside of the tube and is used as the high voltage electrode. A transparent Indium Tin Oxide (ITO) coating was applied to the outer surface of the sapphire tube which acts as both the electrical ground for establishing the electric field as well as the resistive heating element for heating of the refrigerant. Fig. 2 illustrates the electrical wiring of the test section.

A regulated DC power supply (Elektro-Automatik PS8000T) is used to provide current through the ITO coating in order to

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