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Electrohydrodynamic augmentation of a reflux thermosyphon

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ABSTRACT

In this study, a reflux thermosyphon using HFE-7000 as the working fluid is fitted with a concentric electrode in order to investigate the influence of electrostatic forces on the evaporator thermal performance. Importantly, the thermosyphon is constructed from an ITO coated sapphire tube resulting in a thermosyphon enclosure with high thermal conductivity that is electrically conductive and transparent. This allows visualisation of the boiling dynamics within the thermosyphon for both the scenarios where there is no electric field and when electric fields of increasing intensity and frequency are imposed. Results are obtained for two heat fluxes, 8 kW/m^2 and 15 kW/m^2, for applied voltages ranging from 0 kV to 8 kV with AC frequencies between 20 Hz and 100 Hz. Fill ratios for the evaporator of 50% and 100% are considered. The main results show that the evaporator thermal resistance is fairly insensitive to applied electric field strength until it is strong enough to overcome local gravitational forces, and this occurs in the region of 3–4 kV. Subsequent to this the boiling dynamics and resulting heat transfer performance is notably augmented by the Electrohydrodynamic (EHD) forces. For low heat fluxes the evaporator heat transfer coefficient is enhanced up to ~40% for the highest applied voltage. However, for the higher heat flux, the EHD forces result is a substantial deterioration of the heat transfer coefficient, being up to ~70%. The mechanisms responsible for the heat transfer augmentation are discussed in context of the flow visualisation obtained using high speed videography. The opportunity for using an EHD thermosyphon as a thermal potentiometer is also discussed.

1. Introduction

Two phase reflux thermosyphons, sometimes referred to as gravity assisted heat pipes, are sealed tubes that are partially filled with a working fluid. The primary function of a thermosyphons is to transport thermal energy over a distance with a low effective thermal resistance [1]. To achieve this, they rely on the very effective mechanisms of boiling, condensation and latent heat transport. At the heated end, termed the evaporator, heat is transported from the heat source, across the container wall and into the liquid phase of the working fluid where vaporization takes place. The vapour then flows upward to the condenser section where it condenses back to the liquid phase, releasing the latent heat, which is then transported across the tube wall to the heat sink. The condensate is then forced to flow back to the lower evaporator section by gravity. In designing thermosyphon thermal hardware it is thus necessary to have knowledge of the heat and fluid transport mechanisms so that appropriate models can be formulated, and this has been the focus of the preponderance of past thermosyphon research, as recently reviewed by Di Marco et al. [2].

There is a moderate body of work related to enhancing the heat transfer in reflux thermosyphons. These are largely concerned with enhancing the boiling heat transfer using enhanced boiling surfaces or inserts [3,4]. However, these are passive techniques and do not offer the possibility of real-time control of the effective thermal resistance. In fact, the most common method for the control of heat pipes and thermosyphons is by introducing a non-condensable gas (NCG) and varying the effective condenser length by varying the NCG chamber pressure [4–6].

In this work an active method for heat transfer augmentation and control is investigated, that being the use of electrostatic forces to redistribute the phases and thus influence the heat transfer performance. Some benefits over traditional gas-loaded variable conductance thermosyphons is the negligible additional energy requirement, simplicity of installation, rapid response and low cost. The main drawback is that it requires the use of dielectric fluids, such as refrigerants, and a high voltage power source.

Electrohydrodynamics (EHD) involves the application of electric fields to fluids. EHD forces have been studied in two-phase systems, including convective flow boiling enhancement [7–9]. Charging the system with an electric field can dramatically augment the flow regimes, and thus the heat transfer. This augmentation is due

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Nomenclature

Symbol	Description
A_i	surface area (m^2)
Bo	Bond number
Co	confinement number
C_p	specific heat (J/kg K)
D	diameter (m)
E	electric field strength (kV/m)
f	frequency (Hz)
f_e	electric force density (N/m^2)
g	gravitational acceleration (m/s^2)
h	heat transfer coefficient (W/m^2 K)
HV	high voltage (V)
I	current (A)
j_v^*	superficial vapour velocity or vapour production rate
K	constant
k	thermal conductivity (W/m K)
L	length (m)
M_d	Masuda number
N_{lg}	electrogravitational number
P	pressure (bar)
P_{crit}	critical pressure (bar)
P_r	reduced pressure ($P_r = P/P_{crit}$)
Q	power (W)
q	heat flux (W/m^2)
r	radius (m)
Re	Reynolds number
T	temperature (K)
ΔT	temperature difference (K)
t	time (s)
V	voltage (V)
V_f	fill volume (mL or %)
We	Weber number
Greek	
ε	permittivity (N/V^2)
ε_r	relative permittivity or dielectric constant ($\varepsilon_r = \varepsilon/\varepsilon_0$)
ε_0	permittivity of free space ($\varepsilon_0 = 8.85 \times 10^{-12}\ N/V^2$)
λ_c	characteristic bubble length (m)
μ	dynamic viscosity ($N\ s/m^2$)
v	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
ρ_{ei}	charge density (C/m^3)
σ	surface tension (N/m)

to the imposed body forces on the fluid in the presence of an electric field which act to alter the bulk fluid behaviour and also the interaction of phases at the liquid-vapour and solid interface. The three components of the EHD force, namely the electrophoretic, dielectrophoretic and electrostrictive forces, are given by the following expression [10,11],

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

Each of these components contributes to the flow augmentation in different ways. The first term, the electrophoretic force, acts on the net free charge within the fluid promoting bulk motion within the liquid and vapour phases.

The second term, the dielectrophoretic force, can be the most significant in two-phase flows. This force is generated due to the difference in permittivity between the liquid and vapour phases. The mechanism of phase separation of a dielectric fluid under various non-uniform electric fields has been described by Bryan and Sayed-Yagoobi [7]. Of particular relevance in two phase flow is the attraction of the higher permittivity fluid to regions of high electric field strength, and those of lower permittivity (vapour buble) to regions of lower electric field strength. In this way the flow is redistributed based on the electric field strength and permittivity differential of the phases. This behaviour is referred to as liquid extraction and vapour repulsion. At the liquid vapour interface where gradients in fluid properties are very high, the dielectrophoretic force can have a significant influence on the heat transfer as a result of phase redistribution [12]. In two-phase flow scenarios this can result in liquid being pulled from the channel wall, enhancing mixing of the phases, and consequently augmenting the heat transfer.

The final term represents the electrostrictive force which arises from variations of the permittivity with changing density and temperature. Of these three terms it is thought that the second is the most dominant for two phase flow conditions [12], though there exists some debate on this matter.

EHD has been shown to enhance convective boiling in a number of ways. The electric forces increase the number of nucleation sites, the frequency of bubble departure, and the bubble size [13]. In this way, EHD forces result in an improvement of the heat transfer by inducing a more vigorous nucleate boiling regime. As mentioned above, the redistribution of the flow due to liquid extraction augments the bulk fluid motion as well. The liquid is attracted to regions of high electric field strength whilst vapour bubbles are repelled. This is particularly important for horizontal stratified flow scenarios where the liquid flow can be agitated to such an extent as to wet both the top and bottom of the channel, increasing the heat transfer in these regions [9]. It has also been found that the level of heat transfer enhancement is proportional to the applied voltage, but inversely proportional to the working fluid flow rate and applied heat flux [12–14].

Two phase flow augmentation due to EHD has been studied for a wide range of applications and conditions. Comprehensive review studies of EHD in two-phase applications have been compiled by Allen and Karayiannis [11] and more recently by Laohalertdecha et al. [15]. Much of the analysis to date has focussed on two-phase flow boiling augmentation using both AC and DC electric fields, typically in the horizontal orientation. Varying levels of augmentation of the average heat transfer coefficient have been reported in the existing literature.

Cotton et al. [12] investigated the influence of applied DC electric fields in flow boiling using R134a as the working fluid. A flow pattern map was developed for the regimes induced by an applied high voltage of 0–8 kV. A dimensionless analysis was also carried out highlighting the importance of the Masuda number which characterises the body forces associated with EHD, here defined as suggested by the IEEE-DEIS-EHD Technical Committee [16],

$$M_d = \frac{\varepsilon_0 E_0^2 L^2}{\rho_l v_l^2} \tag{2}$$

It was found that the EHD body forces strongly influence the flow when they are large enough to overcome the inertial forces within the system. It was proposed that when $M_d \sim Re^2$ the EHD forces interacted significantly with the liquid phase, thus redistributing the flow. This phase redistribution affected both the observed flow regimes and rate of heat transfer.

A recent study by McGranaghan and Robinson [9] investigated the effects of EHD on horizontal flow boiling with full visualisation of the heated test section. HFE-7000 was used as the working fluid and EHD effects were investigated for an applied 60 Hz AC sinu-