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Experimental study of heat transfer enhancement in electrohydrodynamic conduction pumping of liquid film using flush electrodes

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HIGHLIGHTS

► Significant difference in flow rates has been observed by variation of temperature.
► The effect of temperature increase on enhancement of efficiency is considerable.
► The heat transfer coefficient in case2 increases due to vortices above electrodes.
► The optimum film thickness for heat transfer coefficient enhancement is 6 mm
► Heat transfer and power consumption ratio is decreased up to 10 kV intensively.

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ABSTRACT

Electrohydrodynamic conduction pumping of free surface dielectric liquid film, using flush electrodes, has been studied experimentally for various film temperatures. Volume flow rate, heat transfer and power consumption ratio and conduction pumping efficiency of free surface liquid film in different film thicknesses and temperatures have been investigated and then the best operating conditions have been presented. Also, the heat transfer coefficient on free surface liquid film passing on flush electrodes is compared with similar liquid film in absence of flush electrodes in different temperatures. Results show that as applied voltage increases, significant differences in volume flow rates have been observed by changing the temperature. Applied voltage related to the highest percentage of heat transfer coefficient enhancement demonstrates the reverse relation with temperature. Results confirm that there is a direct relationship between film thickness and the applied voltage related to the maximum heat transfer per pumps power consumption.

1. Introduction

Interaction of electric field with dielectric fluid medium (EHD) can set up a mechanical body-force which can create a flow in the fluid and can be used in various applications such as liquid film pumping, mass transport, heat transfer control, electronic device cooling, and etc.

When a dielectric fluid is exposed to an electric field, three electric body forces which induce the fluid to motion can be expressed as [1]:

$$f_e = \rho_c E_e - \frac{1}{2}E_e^2\nabla\varepsilon + \frac{1}{2}\nabla\left[E_e^2\left(\frac{\partial\varepsilon}{\partial\rho}\right)_T\rho\right] \tag{1}$$

The symbols are defined in the nomenclature. The first term is the force exerting on positive and negative free charges, called Coulomb force (electrophoretic force), the second is dielectrophoretic force which mainly depends on electric permittivity gradient and the third one is electrostrictive force related only to compressible fluids. The forces exist together but it is necessary to note that for a single phase, isothermal medium, the only dominant mechanism to generate a permanent EHD motion is Coulomb force [2]. Moreover, in the present study, due to the low temperature gradient, electric permittivity gradient is negligible.

In the basis of free charges generating process, EHD pumping mechanisms can be classified into three kinds: ion-drag pumping [3–7], induction pumping [8–12] and conduction pumping [13–17]. Ion-drag pumping deals with the direct injection of charges into a dielectric fluid. This mechanism is not very desirable since it can degrade the working fluid [2]. Induction pumping basis is the generation of induced charges due to non-uniformity in electrical

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Nomenclature

E_e	electric field strength [kV/m]
E_p	power consumption [Watt]
V	applied voltage [kV]
I	current [μA]
F_e	electric body force [kg m/s^2]
F_f	friction force [kg m/s^2]
w	channel width [mm]
u_{av}	average velocity [mm/s]
L	length of test channel [mm]
Q_v	volume flow rate [m^3/s]
g	gravitational acceleration [m/s^2]
h	specific energy of open channel flow [m]
Q_h	rate of heat transfer [Watt]
$\overline{h}$	average heat transfer coefficient [W/(m^2 K)]
A	surface area of the film contacted with air [mm^2]
T'_{av}	average temperature of film in case1 and case2 [°C]
T_∞	environment temperature [°C]
$T_{o,av}$	average output film temperatures of case1 and case2 [°C]
$T_{i,av}$	average input film temperatures of case1 and case2 [°C]
$\dot{m}$	film mass velocity [kg/s]
C_p	average specific heat capacity at constant pressure [J/(kg K)]

Greek symbols

ρ_c	charge density [1/cm]
ε	electric permittivity [F/m]
δ	film thickness [mm]
ρ	density [kg/m^3]
μ	dynamic viscosity [Pa s]
η	Pumping efficiency of a liquid film

conductivity of liquid. This non-uniformity can be caused by temperature gradient and/or inhomogeneity of the fluid (in the presence of interface between different liquids phases). Therefore this mechanism is not suitable for isothermal and homogeneous liquid. Conduction pumping is achieved by non-equilibrium behavior of dissociation of molecules within the liquid and recombination of the generated ions. The recombination is in dynamic equilibrium:

$$A^+B^- \xleftrightarrow{k_d,k_r} A^+ + B^- \tag{2}$$

Where k_d and k_r are dissociation and recombination rate constants, respectively. This causes heterocharge layers to be formed in the vicinity of the electrodes under DC electric field. The attraction between each electrode and generated charges in heterocharge layer induces a fluid motion from the liquid side toward the electrode side.

Pumping of liquid films has many industrial applications, including: heat pipes, heat exchangers, enhancing heat transfer in phase change processes, etc. EHD pumping is one of the best methods for liquid film pumping because of low electrical power consumption, ease in manufacturing and controlling technique. Moreover, it is vibration less, soundless and lightweight due to the absence of moving parts.

Induction pumping of liquid films has been studied by few researchers [11,12,18–20]. Pumping of stratified liquid film with electrical conduction phenomenon was introduced by Seyed-Yagoobi et al. [21]. They used two types of electrode pairs: flush mounted and perforated. Their results indicated that flush electrodes are more suitable for thin liquid films, while perforated electrodes are better for thicker liquid films. In other work, Seyed-Yagoobi et al. have studied numerically conduction pumping of dielectric liquid film in the presence of evaporation [22]. Ahmad et al. have studied saturated pool boiling of R-123 including the critical heat flux (CHF). It was enhanced by modifying the surface characteristics and applied a high intensity electrostatic field [23]. They reported that EHD produced a further increase in the heat transfer rates particularly at low heat flux values and near the CHF.

To the best of the author's knowledge, to-date there is no experimental study about the heat transfer on electro-hydrodynamic conduction pumping of dielectric liquid film. In present study, volume flow rate, heat transfer per power consumption and efficiency of free surface liquid film conduction pumping in different liquid temperature and film thicknesses have been investigated and used to determine the best operating conditions. The heat transfer coefficient on free surface liquid film passing on flush electrodes is compared with similar liquid film without flush electrodes in different temperatures.

2. Experimental setup

The schematic of the experimental setup is shown in Fig. 1. Loop consists of two direct channels, Case1 and Case2, one involves flush electrodes and the other measures the fluid volume flow rate inside the loop and compares the heat transfer coefficient with electrode side. These direct channels are connected by means of two semi-circle channels. These semicircle channels are equipped with two flush electric heaters on the floor in order to control the film

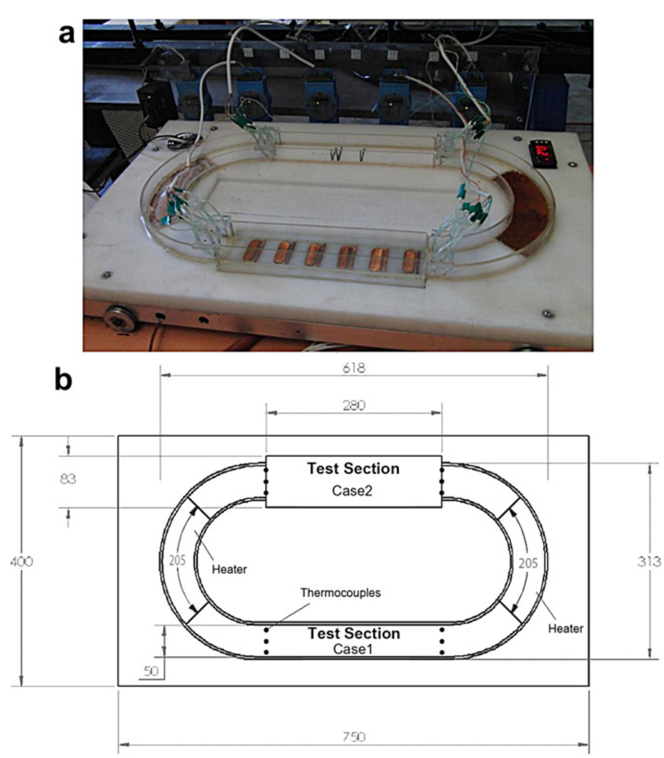

Fig. 1. (a). Photograph of experimental setup. (b). Schematic diagram of experimental setup (dimensions in mm).