Journal of Electrostatics 73 (2015) 71–79

Contents lists available at ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

Experimental investigation of fully developed falling film flow in the presence of conduction pumps

A. Sobhani [a], Sh. Nasirivatan [a], R. Gharraei [b], E. Esmaeilzadeh [a, *]

[a] Heat and Fluid Flow Research Laboratory, Faculty of Mechanical Engineering, University of Tabriz, Tabriz, Iran
[b] Mechanical Engineering Department, Azarbaijan Shahid Madani University, Iran

ARTICLE INFO

Article history:
Received 29 March 2014
Received in revised form
22 September 2014
Accepted 20 October 2014
Available online 7 November 2014

Keywords:
Falling film
Fully developed
EHD
Conduction pumps

ABSTRACT

Conduction pumping is appropriate way for liquid pumping due to its benefits like being noise free and easy controlling. In the present work fully developed falling film flow in the presence of conduction pumps has been experimentally investigated. Two different arrangements were selected and Transformer oil was used. Results indicated that, applying electric field would decrease thickness of falling film in wide range of Re number. The variation of wave's frequency and velocity regarding to Re number is also presented and compared for arrangements. Conduction pumps increased wave's frequency at low Re numbers conversely decreased it at high Re numbers.

Introduction

The study of fluid flow behavior under the effect of electric field is generally referred to electrohydrodynamic (EHD). EHD phenomena has many industrial application and one of them is liquid pumping. In recent years there has been particular concern over liquid pumping using EHD phenomena due to its advantages such as being noise free, vibration less, light weighting, easy controlling, capable for usage in micro scales, etc. Therefore EHD pumping is recognized as one of the best methods for liquid pumping. Generally three electric body forces act on the fluid when a dielectric fluid is exposed to electric field [1].

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

The first term is the Coulomb force which exerts the free charges that are available in dielectric fluid, the second one is the electrophoretic force and it is dependent on electric permittivity gradient which mainly can be observed in the interface of two fluids. The last term is electrostrictive force which deals with density gradient. The density gradient can be exist due to compressibility of fluid or phase change and temperature gradient in the fluid. These forces can occur simultaneously but in isothermal and incompressible single phase fluids it is just the Coulomb force that plays the main role in EHD motion [2].

Mainly the EHD pump operation (in isothermal and incompressible single phase fluids) is based on generating the free charges in the dielectric fluid and exerting them by electric field. Therefore the EHD pumps can be classified in three types according to the procedure that they use for creating free charges: ion-drag pumps [3–7], induction pumps [8–12] and conduction pumps [13–18]. Ion-drag pumping injects charges directly into a dielectric fluid through the sharp electrode. This kind of EHD pumping degrades the working fluid hence the pumping process can't be continuous [2]. Induction pumping deals with charges that are generated as the result of non-uniformity in the working fluid conductivity. This non-uniformity occurs as a consequence of temperature gradient, phase change or inhomogeneity of the fluid. Conduction pumping is associated with dissociation of molecules into positive and negative ions and recombination of the generated ions within a dielectric liquid. Dissociation and recombination processes are related to each other with a dynamic equilibrium:

$$A^+B^- \underset{k_r}{\overset{k_d}{\leftrightarrow}} A^+ + B^-$$

Where k_d and k_r are dissociation and recombination rate constants, respectively. While recombination rate constant does not depend on the electric field intensity, Dissociation rate constant is a function of it and increasing the electric field intensity would increase the magnitude of dissociation rate constant. Therefore when the

* Corresponding author. Tel.: +98 914 116 0374.
E-mail address: esmzadeh@tabrizu.ac.ir (E. Esmaeilzadeh).

http://dx.doi.org/10.1016/j.elstat.2014.10.001
0304-3886/

Nomenclature

f_e	electric force (N)
U_w	wave velocity $\left(\frac{m}{s}\right)$
U_m	flow mean velocity $\left(\frac{m}{s}\right)$
Re	Reynolds number
E	electric field intensity $\left(\frac{N}{C}\right)$
ρ_f	fluid density $\left(\frac{kg}{m^3}\right)$
ε	vacuum permittivity $\left(\frac{F}{m}\right)$
μ	viscosity $\left(\frac{N \cdot s}{m^2}\right)$
θ	inclined surface slope (degree)
k_d	dissociation rate
k_r	recombination rate
Q	volumetric flow rate $\left(\frac{m^3}{s}\right)$
W	inclined surface wide (m)
δ^*_{mean}	non-dimensional flow thickness (mm)
δ_{nus}	Nusselt predicted flow thickness (mm)
f	frequency (Hz)
δ	flow thickness (mm)
υ	kinematic viscosity $\left(\frac{m^2}{s}\right)$

rate of recombination is dominated by the dissociation (according to literature, it happens when the electric field intensity is in the range of $\left(1\frac{KV}{cm} \le E < 100\frac{KV}{cm}\right)$ the electric field affects the free charges generated by dissociation. Hence the free charges are attracted to the electrode with an opposite polarity and the heterocharge layers would be created [18]. According to the polarity of ions and electrodes, two main flows with opposite direction are formed from liquid side toward electrode side in the electrodes heterocharge layer. Since these flows can eliminate each other, the conduction pumps are designed in such a way that the net flow with desired direction be generated.

Siddiqui and Seyed-Yagoobi [19] introduced pumping of stratified liquid film with conduction phenomenon using both the flush and the perforated electrode pair, they concluded that in case of thin liquid film it is better to use flush electrodes while for thicker ones perforated electrodes are more suitable. M. Yazdani and J. Seyed-Yagoobi [20] have done a numerical study on the liquid film flow which was induced electrically dealing with the electrical phenomenon and the theoretical study of Y. Feng, J. Seyed-Yagoobi investigated the EHD conduction pumping phenomenon [21], and these two studies had similar results. So, they found that the flow direction is always from the narrower electrode toward the wider one and the polarity of electrodes does not influence them. M. Yazdani, J. Seyed-Yagoobi [22] have performed the numerical study of on the effects of charge mobility on electric conduction dielectric liquid flow and R. Gharraei et al. conducted an experimental study through which the EHD conduction pumping of various liquid films were investigated [23]. They concluded that mismatch of mobility for positive and negative ions can affect the flow at the same time. The flow direction is dictated by the dominant factor. According to an experimental study done by R. Gharraei et al. about EHD conduction pumping of various liquids film using flush electrodes, main factors in pumping direction and performance were mobility difference and asymmetry of electrodes. Each of these factors becomes dominant in different conditions. In order to have the best operating condition, one can take advantage of the efficiency of free surface. M. Hemayatkhah et al. [24] have investigated flow pattern visualization of liquid film conduction pumping using flush-mounted electrodes. They concluded that for more than one pair of electrodes secondary vortices appears which is caused by the primary one. In this case the vorticity of primary and secondary vortices decreases with the electrode width ratio (because of its weakening effect), while for a pair of electrodes these vortices will increase. R. Gharraei et al. have investigated conduction pumping of dielectric liquid film using flush-mounted electrodes numerically [25]. The ion mobility difference and electrodes configuration have been introduced as two major factors affecting the conduction pump. According to numerical results the dominant factor determines the flow direction in various operating conditions.

the liquid film wavy flow on the vertical or inclined surfaces which occurs in the presence of gravitational field, has been the concern of many studies since it has huge usage in industrial applications like condensers, evaporators, etc. In order to investigate the falling film fluid flow, one may define the flow Reynolds number as [26]:

$$\text{Re} = \frac{4Q}{\upsilon W}$$

Where Re is the Reynolds number, Q is volumetric flow rate, W is channel width and υ is the kinematic viscosity of fluid.

According to Reynolds number, the falling film flow regime may be divided in three zones. The first zone is laminar regime which is usually considered to exist in the Re number range up to 25. The second zone is intermediate regime which contains the laminar flow and exist in the Re number range from 25 up to 1000 [26]. The third zone is the turbulence region which is characterized by flows above a Reynolds number of 1000. The falling film fluid flow on the inclined surfaces can be described as a function of distance from the leading edge of the flow plane. In the beginning of leading edge, there is an acceleration zone in which the flow regime is undeveloped. Following the undeveloped region is a zone which is called the transient region. In the transient region, little or no rippling can be seen and the flow surface is smooth. The smooth flow interface in the transient region quickly develops waves as the result of gravitational field and wall shear stress. This wavy flow region is called the fully developed region.

In 1916 Nusslet published the correlation for the film thickness. He assumed the flow to be rectilinear with a flat interfacial in the steady state system [27]. Lel et al. [28] investigated two different methods for measuring the thickness of wavy films. The first one was a new non-intrusive technique called "chromatic confocal imaging method" and the second method for simultaneous measurements of film thickness and wave velocity was based on a fluorescence intensity technique. The experimental data agreed well with the results from published experimental and theoretical studies. They also presented the new correlation for calculating the mean film thickness which was the enhanced form of Nusselt correlation.

Brauner and Maron [29] discussed the boundary between the smooth film entry region and the wavy region with relation to various operation conditions. They studied the waviness characteristics at the rippled region and their development. Jackson [30] determined the thickness of a falling film by dissolving the radioactive material in the working fluid and measuring the radiation emitted. Jones and Whitaker [31] described a new method for measuring wavelength and wave velocity. They compared their experimental results with a numerical solution of the Orr-Sommerfeld equation and they obtained a Good agreement in the region near the top of the film where small disturbance theory is expected to be valid. Moran [26] investigated instantaneous hydrodynamic characteristics of laminar falling films of silicone oil on an inclined plate using a photochromic dye activation technique