International Journal of Heat and Mass Transfer 118 (2018) 976–988

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Optimization of the wire electrode height and pitch for 3-D electrohydrodynamic enhanced water evaporation

Jin-Sheng Leu [a], Jiin-Yuh Jang [b,*], Yi-Hsuan Wu [b]

[a] Department of Mechanical Engineering, Air Force Institute of Technology, Kaohsiung 82042, Taiwan
[b] Department of Mechanical Engineering, National Cheng-Kung University, Tainan 70101, Taiwan

ARTICLE INFO

Article history:
Received 15 June 2017
Received in revised form 4 November 2017
Accepted 12 November 2017

Keywords:
Corona wind
Optimization
EHD
Evaporation

ABSTRACT

In this study, numerical and experimental analyses were carried out to study the electrohydrodynamic (EHD) effect on the evaporation rate of a channel forced convection flow. Three-dimensional steady turbulent flow equations combined with Maxwell equations were solved. The optimization of the electrode height (H) and longitudinal pitch (SL) was investigated numerically along with an optimal strategy (SCGM, simplified conjugate-gradient method). The mass transfer gain per power consumption was taken as the objective function to be maximized. The results showed that the EHD effect on the evaporating rate increased with increases in applied voltage and electrode pitch (SL) and decreases in electrode height (H). For example, as air flow inlet velocity $u_{in} = 1$ m/s and applied voltage $V_0 = 15$ kV, the mass transfer enhancement was doubled for $SL = 40–100$ mm at $H = 20$ mm, while the mass transfer enhancement was 3.5 times greater for $H = 30–15$ mm at $SL = 100$ mm. In addition, the optimization analysis indicated that the mass transfer gain enhanced per Watt power consumption by 316.9–179.7% when combined with the optimal (H, SL) design ranging from $V_0 = 13$ to 17 kV and $u_{in} = 1.0$ m/s. The comparisons of numerical results and experimental data obtained satisfactory consistency within a discrepancy of 19%.

1. Introduction

Liquid evaporation is an effective latent heat transfer mechanism widely utilized in industrial fields for such things as chemical distillation, air conditioning, cooling towers, and drying. Thus, enhancement of evaporation performance has been the subject of many industrial and academic research studies. Enhanced techniques work based on disturbing the distribution of the velocity across channels by use of secondary flows. Secondary flows can be generated using passive methods including extended surfaces (wavy, louver, or offset strip fins) and vortex generators or by active methods that require additional energy input. Electrohydrodynamics (EHD) has been shown to be a novel active heat enhancement technique. The mechanism is attributed to the EHD-induced secondary flow (corona wind or ionic wind) resulting from the emitting electrode to the ground plate, which serves as a corona jet that breaks and destabilizes the velocity boundary layer. The net effect is the additional mixing of fluids and destabilization of the boundary layer, which leads to a substantial increase in either the heat transfer or moisture removal rates. The advantages of EHD include a quick response to control the flow, low power consumption, absence of noise, and the fact that production can occur at room temperature and at atmospheric pressure. This makes EHD one of the most promising methods among various heat and mass transfer enhancement techniques.

In the past several decades, there have been many studies on EHD-induced heat transfer enhancement. Laohalertdecha et al. [1] made a complete review of EHD-induced heat transfer enhancement, clearly describing the EHD effect in single-phase flows (air and liquid) and phase change flows (condensation, boiling). Ohadi et al. [2] studied EHD-induced heat transfer enhancement of forced convection pipe flow. Results have been reported for parametric values of the Reynolds number (1000–15,000), electric field potential (<7.75 kV), and number of electrodes (single or double electrode configurations). It has been found that heat transfer enhancements are significant only in the laminar and transitional flow regimes when using a single electrode, while with a two-electrode configuration, enhancements can extend to the turbulent flow regime. Shakouri and Esmaeilzadeh [3] explored the EHD enhancement effect of 3D-shape heat sources placed in horizontal channels using different electrode arrangements. Lin and Jang [4] discussed the 3D EHD effect of the flow field and heat enhancement on a plate-fin heat exchanger. Deylami et al. [5] numerically studied 2-D forced convection heat transfer enhancement with the EHD turbulent flow technique inside a smooth

---

* Corresponding author.
E-mail address: jangjim@mail.ncku.edu.tw (J.-Y. Jang).

https://doi.org/10.1016/j.ijheatmasstransfer.2017.11.056
0017-9310/© 2017 Elsevier Ltd. All rights reserved.

Nomenclature

b_{ion}	ion mobility of air ($m^2\,V^{-1}\,s^{-1}$)
C	water vapor mass fraction in air ($kg_{water}\,kg_{air}^{-1}$)
C_{in}	water vapor mass fraction at the inlet ($kg_{water}\,kg_{air}^{-1}$)
C_{ws}	water vapor mass fraction at the wetted surface ($kg_{water}\,kg_{air}^{-1}$)
D	mass diffusivity ($m^2\,s^{-1}$)
D_e	diffusion coefficient of ions ($m^2\,s^{-1}$)
E	electric field strength ($V\,m^{-1}$)
H	electrode height (mm)
h_m	mass transfer coefficient (ms^{-1})
$\overline{h}_m$	averaged mass transfer coefficient (ms^{-1})
J	current density ($A\,m^{-2}$)
J_{obj}	objective function
L_x	length of the water surface (mm)
L_y	height of the channel (mm)
L_z	width of the channel (mm)
$\dot{m}$	mass transfer rate at the wetted surface ($kg\,s^{-1}$)
P	pressure (Pa)
Sh	Sherwood number, $Sh = \overline{h}_m L_x/D$
Sh_0	Sherwood number without EHD effect, $Sh = \overline{h}_m L_x/D$
SL	electrode longitudinal pitch (mm)
u_{in}	inlet frontal velocity (ms^{-1})
V	applied voltage (electric potential) (V)
V_0	applied voltage (electric potential) at the wire (V)
u, v, w	velocity of air stream along x, y, z coordinates (ms^{-1})
x, y, z	coordinate (m)
x_1, x_2	design variables

Greek symbols

β	descent direction coefficient
γ	conjugate-gradient coefficient
ε_0	electric permittivity of fluid ($C^2\,N^{-1}\,m^{-2}$)
ε	dissipation rate ($m^2\,s^{-3}$)
κ	turbulent kinetic energy ($m^2\,s^{-1}$)
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
ρ_c	space charge density (Cm^{-3})
ξ	search direction for design variable

Subscript

k	iteration step in the optimization process
in	air inlet

channel. The swirling flow pattern in the presence of an electric field has also been studied. The results demonstrates that when using multiple electrodes, the variations in the electrode arrangements induce significant improvement in the heat transfer coefficient. Peng et al. [6] investigated heat transfer enhancement in a rectangular channel using EHD. The study focused on the effects of longitudinal position for a single electrode, the longitudinal arrangement of multiple electrodes, and the electrode number with an optimal longitudinal arrangement. The results showed that the closer the electrode is to the inlet, the more effective it is for heat transfer enhancement. The design criteria for the optimal electrode configuration with multiple electrodes was shown to make the electrodes uniformly cover the entire channel in the longitudinal direction. Recently, Wang et al. [7] proposed an effective electrode pair arrangement in a rectangular double-wall-heated channel, where one electrode impinged on the top wall, and the other impinged on the bottom wall. This arrangement can eliminate “extra electric body force” and remove the “barrier effect”. The EHD-enhanced heat transfer performance was 166.4% for the top wall and 242.7% for the bottom wall.

In the literature concerning EHD applied in phase change problems, Singh et al. [8] undertook a comprehensive review of EHD-induced evaporation and drying in the context of food and bioprocessing industries. The authors concluded that the EHD process has huge potential as an alternative to conventional drying processes. The low costs involved in its implementation and maintenance make it an ideal process for industries. However, the design of a continuous EHD system will require an extensive understanding of the mechanism in terms of the cost and energy required for implementation of the process at an industrial level. Hashinaga et al. [9] applied the EHD technique to elevate the drying rate of apple slices. It was found that the ionic wind produced by the needle electrode could provide higher drying efficiency than a normal air-cooled system. Lai et al. [10,11] discussed the problem of water evaporation and food drying with different electrodes. The experimental results showed that with the EHD effect, the Sherwood number (*Sh*) can be increased 3–4 times. Recently, Huang and Lai [12] discussed the EHD effect applied to a two-dimensional horizontal forced convection channel flow and explored different inlet speeds and applied voltages on the water evaporation rate. Heidarinejad and Babaei [13] numerically investigated the EHD effect on the enhancement of the water evaporation rate in a channel. The coupled equations of a one-wire electrode system, flow field, temperature field and species concentration fields were solved simultaneously via the SIMPLE algorithm and the Kaptsov hypothesis. Bardy et al. [14] studied the dehydration of a food product by means of conventional forced convection drying verses EHD drying methods using three different wire-electrode configurations. It was concluded that EHD drying can yield the same drying rate as forced convection drying, but with significantly lower airflow velocities, and therefore higher exergetic efficiencies.

Based on the foregoing literature review, it can be inferred that the EHD technique is an effective method by which to promote the heat and mass transfer rates in both external and internal convection flows. However, a suitable electrode system requires a complete evaluation of the operating parameters, including the electrode configuration (arrangement, electrode number, and polarity), flow conditions (inlet velocity, temperature, and concentration), and electric field attributes (applied voltage, charged density, and the corona current at the electrodes). In addition, Refs. [5–7] have clarified that electrode configuration parameters (electrode pitch, electrode height, and electrode number) are coupled with each other and thus have significant influences on the heat transfer enhancement. Accordingly, a numerical optimization technique for the electrode configuration necessary to obtain optimal evaporation performance with reasonable power consumption is needed. In the present study, in addition to an investigation of the EHD effect on the mass transfer of a 3-D turbulent forced convection channel flow using both experimental and numerical methods, an analysis of the optimal electrode location is attempted using the simplified conjugate-gradient method (SCGM) [15]. Concerning the recent literature including optimal design procedures applied in industrial applications, the Taguchi method [16], Pareto method [17], and the fixed interference method (FIM) [18–21] are practical optimal strategies. The SCGM method proposed by Cheng and Chang [15] extends the conjugate-gradient method (CGM) [22]