Optimal and Experimental Analysis of Electrohydrodynamic Enhancement of Water Evaporation

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Abstract. The paper investigates the EHD effect on the evaporating rate of the water surfaces by numerical and experimental methods. Two-dimensional turbulent forced convection channel flow is theoretically analyzed. Parametric evaluation including the applied voltage, electrode location is executed in details. The related optimization of the electrode pitch and height for specified input voltage is investigated numerically along with a simplified conjugated-gradient method (SCGM). The results show the EHD effect on the evaporating rate is increased with increase of voltage and electrode pitch and decrease of electrode height. In addition, based on the per unit power consumption, the best mass transfer performance is obtained at the optimal electrode location for each input voltage case. At last, the numerical results get a good consistency with the experiment within a discrepancy of 27%.

Introduction

Electrohydrodynamic (EHD) enhancement utilizes electrodes to generate a high electric field in the dielectric fluid to ionize the working fluid and generate the Corona discharge. The ions are driven toward or sucked back from the ground device by the Coulomb force. During the migration processes, these ions transfer the momentum to the fluid by collision and disturb the fluid stream (ionic wind).


In the literature on mass transfer, Hashinaga et al. [5] 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 normal air-cooled system. Lai et al. [6,7] discussed the problem of water evaporation and food drying with different electrodes. The experimental results show that the Sherwood number (Sh) with EHD effect can be increased by 3-4 times. Huang and Lai [8] discussed the EHD effect applied to the two-dimensional horizontal forced convection channel flow and explored the different inlet speed and applied voltage on the water evaporating rate.

The foregoing literature review shows that the previous research of EHD technology applied to the mass-transfer performance is mainly based on the experimental and two-dimensional numerical analysis. The present study focused on the EHD effect on the 2-D turbulent forced convection flow and mass transfer by the experimental and numerical methods. The optimal electrode location are attempted to obtain by the SCGM method [9]. Consequently, the experiment will compare with the numerical simulation to verify the accuracy of numerical method.
Theoretical Analysis

Fig 1 designates the physical model. The air velocity and the concentration of water vapor at inlet are shown as \( u_\infty \), \( C_\infty \). Wire electrodes are set above the wetted surface. The longitudinal electrode distances (SL) of ranging 40 ~ 100 mm are applied. The range of wire electrode height (H) is 15-25 mm. The length (Lx) of wetted surface are 310 mm, 390 mm, 470 mm, 550 mm, and 630 mm for different cases. The width (Lz) and height (Ly) of the channel is 150 mm x 100 mm.

![Figure 1. The Physical Model.](image)

To solve effectively the governing equations, the following assumptions are used:
1. The flow is steady state.
2. The fluid physical properties are constant.
3. The electric field is one-way coupled to the flow field. That is, the electric field influences over the flow field, but not vice versa.
4. Diffusion current is omitted from the calculations.

**Electric field equations**:
The electric potential \( V \) is governed by Poisson's equation expresses as :

\[
\nabla^2 V = \frac{-\rho_e}{\varepsilon}. \tag{1}
\]

The electric field strength is defined by :

\[
\vec{E} = -\nabla V. \tag{2}
\]

Current continuity equation is calculated by :

\[
\nabla \cdot \vec{J} = 0. \tag{3}
\]

Ohm’s law is given by :

\[
\vec{J} = \rho_e b_{ion} \vec{E}. \tag{4}
\]

Combine (3) and (4) then

\[
\nabla \cdot (\rho_e b_{ion} \nabla V) = 0. \tag{5}
\]

Expand (5) then the following equation is obtained:
\[
\frac{\rho_c^2}{\varepsilon_0} - \nabla \rho_e \cdot \nabla V = 0.
\]  

(6)

*Flow field equations:*

Continuity equation is given by:

\[
\frac{\partial \Pi}{\partial x_i} = 0.
\]

(7)

Momentum equation is given by:

\[
\frac{\partial}{\partial x_i} \left( \frac{\rho u_i u_j}{\rho} \right) = - \frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_j} \left( \nu \frac{\partial u_i}{\partial x_j} - \frac{u_i u_j}{\rho} \right) + \frac{\rho - E_i}{\rho}.
\]

(8)

*Species conservation equation:*

Conservation equation of water vapor concentration field is given by:

\[
\frac{\partial}{\partial x_i} \left( \frac{\rho u_i C}{\rho} \right) = \frac{\partial}{\partial x_j} \left( D \frac{\partial C}{\partial x_j} - \frac{u_j C}{\rho} \right).
\]

(9)

In above equations, \(\varepsilon\) is the electric permittivity of the fluid \((coul^2/N \cdot m^2)\), \(E\) is the electric field strength \((V/m)\), \(\rho_e\) is the electric charge density \((coul/m^3)\), \(b_{in}\) is the mobility of ions in an electric field \((m^2/V - s)\), \(D\) is the mass diffusivity of water vapor in air \((m^2/s)\). The mass transfer rate (evaporating rate) is calculated by the following equation.

\[
\dot{m}_{ws} = -D \frac{\partial C}{\partial y} = h_m \left( C_{ws} - C_{in} \right).
\]

(10)

The average mass-transfer coefficient is given by:

\[
\overline{h_m} = \frac{1}{L_x \times L_z} \int_0^{L_x} \int_0^{L_z} h_m \, dx \, dz.
\]

(11)

The Sherwood number is obtained by:

\[
Sh = \frac{\overline{h_m} L_x}{D}.
\]

(12)

In above equations, \(\dot{m}_{ws}\) is the mass transfer rate at the wetted surface \((kg/s)\), \(C_{ws}\) and \(C_{in}\) are the concentration of water vapor at the wetted surface and the inlet \((kg_{water}/m^3)\).

*Boundary conditions:*
Air enters the inlet at a uniform velocity (1 m/s) and species (water vapor). No slip conditions are imposed for velocity at walls. The boundary conditions for the potential (voltage) are a Dirichlet condition at the wire electrodes (V=10000~18000 V) and along the grounded electrode (wetted surface) (V=0), and also a Neumann condition elsewhere (∂V/∂n=0). The boundary conditions to determine the charge density at the wire electrode is found by experimental data. The boundary conditions for the concentration are relative humidity 40% and 100% at the inlet and the wetted surface, which means mass fractions of the water vapor are 0.009 (kg water/kg air) and 0.0225 (kg water/kg air).

**Optimization analysis:**

In the present study, the simplified conjugate-gradient method (SCGM) combines with a finite difference/volume method code as an optimizer to search the optimum electrode distance (SL) and electrode height (H). The objective functions $J_{obj}(x_1,x_2)$ are defined as $((Sh/Sh0)/Power)$. The SCGM method utilizes a direct numerical sensitivity analysis to evaluate the gradient of objective function, and suggests a new conjugate direction for the updated design variables. The initial guess for the value of each search variable is made, and in the successive steps, the conjugate-gradient coefficients and searched direction are evaluated to estimate the new search variables. The solutions obtained from the finite difference method are then used to calculate the objective function, which is further transmitted back to the optimizer for calculating the next searching direction until the maximum objective function is obtained.

**Numerical Method**

In this study, the commercially available finite volume method software, namely, the CFDRC (CFD Research Crop, Huntsville, AL) [10] was used to carry out CFD simulations. First, assume voltage and charge density at the wire electrodes. Second, solve the Poisson equation (1) and Current continuity equation (6) to get the electric field. Third, import the electric field data to momentum equation (8) and solve the velocity and concentration fields with SIMPLEC METHOD.

**Results and Discussions**

In order to verify the accuracy of numerical results, the experiment is designed to provide a positive voltage for five wire electrodes above the wetted surface. The copper plate under the water container is the grounded electrode. The constructed experiment apparatus is shown in Fig. 2. The tested cases and corresponding power consumptions are tabulated in Table 1. The experiment then executes about one hour each case to measure the evaporation loss of the water container and compares with the corresponding numerical result.

![Figure 2. The Constructed Experiment Apparatus.](image)
Table 1: Power Consumption for Different Electrode Distance (14000 V).

<table>
<thead>
<tr>
<th>SL [mm]</th>
<th>H [mm]</th>
<th>ground current [µA]</th>
<th>power [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>25</td>
<td>2.74</td>
<td>0.038</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>10.29</td>
<td>0.144</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>21.38</td>
<td>0.299</td>
</tr>
<tr>
<td>60</td>
<td>25</td>
<td>6.56</td>
<td>0.092</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>13.27</td>
<td>0.186</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>47.89</td>
<td>0.670</td>
</tr>
<tr>
<td>80</td>
<td>25</td>
<td>3.35</td>
<td>0.047</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>12.49</td>
<td>0.175</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>43.73</td>
<td>0.612</td>
</tr>
<tr>
<td>100</td>
<td>25</td>
<td>3.12</td>
<td>0.044</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>11.64</td>
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<tr>
<td></td>
<td>15</td>
<td>45.44</td>
<td>0.636</td>
</tr>
</tbody>
</table>

Before the beginning of the experiment, the current-voltage (I-V) diagram of the corona effect should be completed first. Fig. 3 shows the generated corona current at a range of input voltage (10000 V~18000 V) until the collapse voltage happens. The error of numerical result compared with the experiment is within 15%.

Throughout the experiments of establishing electric field characteristics, the charge density at the electrodes are achieved for specified electrode locations. The distribution of charge density for the evaluated range of electrode distance and height is shown in Fig. 4. These values will be set to the specified boundary values at the electrode while the fluid flow equations are solved.

The EHD effect on the flow and water evaporating rate at different electrode location (SL=40 mm, 100mm, H=20mm, 25mm) are shown in the Fig. 5 and Fig.6. From the two figures, it shows that the EHD effect on the flow and concentration boundary layers for electrode distance (SL) 40 mm are stronger than the cases of SL=100 mm. But the influent regions of SL=40 mm are limitedly small than the case of SL=100 mm. In addition, the two figures show that the lower electrode cases (H=20 mm) possess stronger EHD effect than the cases of higher electrode case (H=25 mm). In conclusion, the case of SL=100 mm and H=20 mm infers the highest EHD effect than the other three cases.

Figure 3. The Corona Current vs. Applied Voltage Diagram.

Figure 4. The Charge Density Distribution (14000V).
Fig. 7 presents the related quantitative comparisons following the Figs. 5 and 6. It displays the Sherwood number (Sh) versus different applied voltages for the above mentioned four cases. It can be seen that Sh enhances with increase of the electrode distance and applied voltage, but decreases with increase of electrode height. In addition, the numerical results agree with the experimental results, and the error is within 27%, found in the case of SL=100 mm and H=20 mm.

Fig. 8 discusses the optimization analysis of the electrode location at 14000 V. The objective function $J_{\text{obj}}$ is defined as $((\text{Sh}/\text{Sh}_0)/\text{Power})$. Power means the power consumption, achieved by voltage × ground current (the current through the copper plate). Sh0 means the related situation without EHD effect. Table 1 shows the related power consumption for different electrode location cases. Thus, $J_{\text{obj}}$ illustrates the mass transfer gain per unit power consumption from the EHD effect. Fig. 8 shows that $((\text{Sh}/\text{Sh}_0)/\text{Power})$ exists an optimal value within the evaluated region of electrode location. And the optimal value is obtained at the case of SL=56 mm and H=19.5 mm for around 20 iterations.
Conclusion

The paper studied the EHD effect on the evaporating rate of the wetted surfaces in a forced convection channel flow by numerical and experimental methods. The numerical simulation is carried out by using the two-dimensional turbulent flow to solve the charge density field, velocity field and concentration field. The results show that the Sherwood number is increased with increase of applied voltage. In addition, based on the mass transfer gain per unit power consumption, an optimal electrode location (SL=56 mm and H=19.5 mm) exists for applied voltages 14000 V. Finally, the discrepancies between the experiment and numerical simulation are within 27%.

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References


