Free Convection Heat Transfer in Open System with and without Electrohydrodynamic Enhancement

Abstract
In the food manufacturing industry, food is often dehydrated to a certain moisture content to increase shelf life and reduce packaging for storage and transportation. Typical food drying processes are usually energy intensive due to the use of dehumidified air at high velocities to remove moisture by forced convection. One method of food dehydration that reduces overall energy consumption compared to forced convective drying is Electrohydrodynamic drying (EHD). This method uses a wire-electrode suspended above the food product supplied with a high voltage. The electron flow through the air creates corona wind that causes a convection air current. This creates a secondary airflow directly above the food product. The primary airflow can therefore be lowered since the primary drying mechanism becomes the secondary airflow. The purpose of this study is to demonstrate the use of a student developed experimental system used to study the effects of EHD convection and compare results with past published studies. This was accomplished by comparing the heat transfer coefficient of four electrode wire configurations with and without EHD enhancement. In the experiment, the heat transfer coefficient with EHD enhancement was expected to improve with increasing voltage. The experiment showed that as voltage increased, the benefit of EHD enhancement would also improve, but at a reduced rate. In addition, a single wire electrode was shown to produce the greatest improvement to heat transfer using EHD when compared to two wire electrodes. Finally, the same EHD enhanced heat transfer coefficient could be achieved by different electrode configurations and voltages. These results are comparable to other studies in EHD enhancement, thus showing that the system created can be used to further studies in EHD convection.

Keywords
Food drying, electrohydrodynamic, open system, heat transfer, free convection

Introduction
Drying food to reduce moisture content is an energy intensive operation. The primary purpose of drying food is to reduce the amount of water to improve shelf life, reduce packaging, and reduce the transportation cost of foods [1]. However, many food drying processes are energy intensive, accounting for 12 – 20% of energy consumed in the manufacturing industry [1]. Thus, energy efficient processes that avoid adversely affecting the properties of products are of industrial interest [2]. Even with novel solutions to reduce energy consumption, 85% of industrial dryers utilize convection with hot air or combustion gases as the heat transfer medium. [3]. Specifically, using air as a heat transfer medium results in high energy consumption due to the high velocities necessary to effectively remove moisture in batch systems [4].

One of the methods to reduce the energy required in convective drying is Electrohydrodynamic (EHD) convection. EHD convection results from a phenomenon caused by an electrode carrying a high voltage over a grounded plate creating a corona discharge [5]. The high voltage causes charged particles to disrupt the flow of air, creating a corona wind [2]. The corona wind results in an increase of heat and mass transfer while not affecting the properties of the food product [2]. The effectiveness of EHD convection is dependent on the electric field strength, as the high voltage
flowing through an electrode must cause a flow of charged particles though the high resistance air. In addition, the ionization region is limited by the electric field strength [6].

In 2006, the Mechanical Engineering Department and the European Study Center (ESC) launched a program in Nantes, France, to allow mechanical engineering students to study abroad. The ESC collaborates with Oniris to enhance the experience of students. Oniris is an institution of higher education that concentrates on food science engineering and veterinary science. It is an affiliate with the French Ministry of Agriculture. Students have structured opportunities in the fall to interact with Oniris students and faculty through joint classes and social activities. [7]

Starting in 2015, the Electrical and Computer Engineering Department completed a series of curriculum adjustments to allow senior electrical engineering students to be added to the ESC program and spend their fall semester at the ESC. During this time, electrical engineering students begin their senior design project. These projects are carried out in cooperation with Oniris. [7]

In addition to a study abroad partnership, research is also conducted in collaboration between faculty in the area of EHD drying. Research has taken place largely at the Oniris campus with on-site participation by faculty and students studying abroad. A two-phase project was created for a new EHD drying system to be used in tandem with a team at Oniris after studying abroad. This would improve the ESC program through further collaboration and provide independent research opportunities for future mechanical engineering students.

In 2016, Cleary et al. created an experimental system to study EHD enhancement in an open test section with free convection [8]. The experimental system was similar to the one at Oniris. However, Oniris utilized a closed system with forced convection. The first phase of the project was to use the EHD system originally designed by Cleary et al. to begin research of EHD.

The second phase of the project is to complete an experimental set-up that replicates the closed system, forced convection EHD experiments performed at ONIRIS University. This phase requires an air-handling system that can integrate with the EHD system previously created. In 2018, Brown et al. developed and built an air-handling system to be used with the design by Cleary et al. [9]. This system consisted of an airflow channel with a controlled airflow velocity and psychrometric air properties.

The objective of this study was to demonstrate that the first phase was successful. That is, the system originally created to study EHD enhancement in an open system could produce results similar to other studies. This will allow the study of EHD convection to continue for future engineering students by use of a forced convection chamber. To accomplish the objective, the heat transfer coefficient created by EHD enhancement was measured in different electrode wire configurations and compared with the results in other studies.
Experimental Setup

The experimental set-up consisted of an open test section of 30cm x 30cm x 30cm that allowed free convection with and without an electrostatic field (figures 1 and 2). Figure 1 shows the experimental set up outside the open test section. Copper wire-electrodes (35 SWG tinned annealed) were connected to a high voltage generator to create an electrostatic field.

Figure 1: Schematic of the experiment set up.

Figure 2 shows the experimental set up inside the open test section, as well as the placement of the sensors. Four ABS 3D printed dowels were created for the testing fixture. Each dowel had notches in increments of 1cm. These notches allowed the wire electrodes to be wrapped around a notch, thus keeping the wire taught above the hot plate. The dowels were mounted on ABS slides, allowing a set of electrodes to be separated a specified distance. The hot plate measured 15cm x 15cm, with a 22.45cm x 22.45cm polystyrene board attached underneath it (figure 2). The hot plate and polystyrene were mounted to the frame of the test section, directly below the sliders. The hot plate was connected to its own power supply and was grounded through the high voltage power supply.
As shown in figure 2, the first thermistor measured the temperature between the plate and polystyrene ($T_{top}$). The second thermistor was mounted on the bottom of the polystyrene for the purpose of measuring the steady state temperature of the polystyrene ($T_{bot}$). The infrared sensor mounted above the test section measured the average temperature on top of the hot plate ($T_s$). As shown in figure 1, the final thermistors were mounted to the wall of the lab to measure the wall temperature ($T_w$) and near the DAQ unit to measure the ambient temperature of the room ($T_a$). In addition, a data acquisition unit (LabJack DAQ) was used to collect the output of three thermistors, an infrared sensor, and a hygrometer. The DAQ unit was also used to record and control the applied voltage ($V_p$) and current of the high voltage generator. In addition, the DAQ unit recorded the voltage of the hot plate voltage supply. The relative humidity was measured by a hygrometer mounted above the DAQ unit, it was recorded to ensure that tests were comparable.

Figure 3 shows the thermodynamic system including of all the variables used to calculate the heat transfer coefficient caused by the EHD convection over the hot plate. The total heat flux can be expressed as a combination of the three modes of heat transfer:

\[ \phi = \phi_{rad} + \phi_{conv} + \phi_{cond} \]
\[ \phi_T = \phi_{\text{conv}} + \phi_{\text{cond}} + \phi_{\text{rad}} \quad (1) \]

The convective, conductive and radiative heat flux can be expressed as shown in equations (2) – (4).

\[ \phi_{\text{conv}} = h(T_s - T_a) \quad (2) \]
\[ \phi_{\text{cond}} = \lambda(T_{\text{top}} - T_{\text{bot}}) \quad (3) \]
\[ \phi_{\text{rad}} = \sigma \varepsilon (T_s^4 - T_a^4) \quad (4) \]

The only sources of power for the system were from the hotplate and electrode. Thus, the total heat flux must have been related to the power supplied to the system. Because the electrode was used to produce EHD convection, its effects were accounted for in the heat flux due to convection. Therefore, the total heat flux can be expressed using the following equation:

\[ \phi_T = \frac{P_p}{S_p} = \frac{V_p^2}{S_p R_p} \quad (5) \]

Combining equations 1 through 5, the heat transfer coefficient can be found by:

\[ h = \frac{V_p^2}{S_p R_p} \frac{\lambda}{T_{\text{top}} - T_{\text{bot}}} - \sigma \varepsilon (T_s^4 - T_a^4) \frac{1}{(T_s - T_a)} \quad (6) \]

Experimental Procedure

The increase in heat transfer caused by the EHD effect was studied for four different wire electrode configurations was shown in Table 1. The first configuration was a single wire electrode extended over the hotplate. The three other configurations included two wire electrodes running parallel to each other separated by a specified distance. The two wire configurations were separated by 2cm, 6cm and 10cm respectively from each other. All configurations include three separate electrode heights of 4cm, 6cm, and 8cm from the hot plate, totaling twelve different iterations.

**Table 1: Configurations and number of trials for EHD experiment**

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Number of trials</th>
<th>Distance between electrode and hotplate (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 wire-electrode (Configuration A)</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>2 parallel wire-electrodes 2cm apart (Configuration B)</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>2 parallel wire-electrodes 6cm apart (Configuration C)</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>2 parallel wire-electrodes 10cm apart (Configuration D)</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>8</td>
</tr>
</tbody>
</table>
Once a wire-electrode configuration was set-up, the hot plate was supplied with 12 volts from a power supply for 20 minutes to allow the polystyrene to reach a steady state temperature. This gave a hot plate temperature of 49°C when no EHD enhancement was created. During that time, the high voltage generator ran at 120V, the minimum allowed by the generator, to prevent EHD convection. Once the 20 minutes passed, an initial heat transfer coefficient ($H_o$) was recorded. After the initial heat transfer coefficient was measured, a high-voltage was applied to the wire-electrode until a current was established between the wire-electrode and the grounded plate (threshold voltage). For safety reasons, the system would shut down if the current increased above 300 mV. The high voltage supplied to the wire-electrode was kept constant for a total of 40 minutes, allowing the polystyrene to reach a steady state temperature. After the 40 minutes lapsed the voltage supply to the wire-electrode was then increased an increment of 2 kV over 5 minutes. This was repeated for a voltage range of 8 – 26 kV. At each voltage increment, the temperatures and voltages were recorded every minute for 30 minutes (the time necessary for the to reach a steady state temperature at the bottom of the polystyrene). The final 10 minutes of data recorded during the 30-minute time period was averaged and used to compute the heat transfer coefficient for a specified voltage input ($H_i$). A ratio was then computed to compare the heat transfer coefficient by EHD enhancement to that of pure convection ($H_i/H_o$, heat transfer coefficient ratio).

**Results and Discussion**

Figure 4 shows four plots of the heat transfer coefficient ratio ($H_i/H_o$) as a function of the input voltage (kV). Each of the four plots represents one of the four different wire-electrode configurations at varying electrode heights. Each point represents the average $H_i/H_o$ calculated over a 10-minute period during which all temperature measurements were at steady state. Figure 4 (a) shows $H_i/H_o$ for a single wire-electrode configuration at a height of 4 cm (blue circles), 6 cm (red squares), and 8 cm (green triangles) above the hot plate. Figures 4 (b), (c), and (d) show $H_i/H_o$ for a double wire-electrode configuration, separated by 2 cm (b), 6 cm (c) and 10 cm (d) from each other.
As shown in Figure 4, as voltage increased, $H_i/H_o$ increased as well. For each wire-electrode configuration there was a certain point when the continued increase in voltage did not result in the same rate of increase of $H_i/H_o$. The value at which a 2kV increase in voltage would result in less than a 25% increase in $H_i/H_o$ for a configuration was specified as the transition point. There, after the transition point, further 2kV increases in voltage would result in less than a 20% increase towards $H_i/H_o$. Table 2 shows the average relative humidity of each of the configurations, the maximum recorded $H_i/H_o$, $H_i/H_o$ at the transition point, and the voltage applied to the electrode at the transition point for each of the configurations and electrode heights.
Table 2: Average relative humidity, maximum recorded heat transfer coefficient ratio, heat transfer coefficient ratio and voltage at the transition point for each experimental case.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Distance between electrode and hotplate (cm)</th>
<th>Relative humidity (%)</th>
<th>Maximum heat transfer coefficient ratio (H_i/H_o)</th>
<th>Heat transfer coefficient ratio at transition point (H_i/H_o)</th>
<th>Voltage at transition point (kV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 wire-electrode (Configuration A)</td>
<td>4</td>
<td>11.45±1.61</td>
<td>5.19±0.30</td>
<td>3.83±0.01</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>12.53±2.05</td>
<td>5.82±0.04</td>
<td>3.93±0.19</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>13.87±3.10</td>
<td>5.45±0.16</td>
<td>3.56±0.07</td>
<td>16</td>
</tr>
<tr>
<td>2 parallel wire-electrodes 2cm apart (Configuration B)</td>
<td>4</td>
<td>14.03±0.95</td>
<td>4.56±0.03</td>
<td>4.20±0.05</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>14.81±0.39</td>
<td>4.50±0.06</td>
<td>3.81±0.14</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>15.18±2.17</td>
<td>4.61±0.04</td>
<td>3.12±0.11</td>
<td>16</td>
</tr>
<tr>
<td>2 parallel wire-electrodes 6cm apart (Configuration C)</td>
<td>4</td>
<td>23.23±4.15</td>
<td>4.84±0.07</td>
<td>4.35±0.07</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>20.39±2.28</td>
<td>5.10±0.00</td>
<td>4.81±0.06</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>15.87±1.21</td>
<td>4.89±0.18</td>
<td>3.80±0.15</td>
<td>18</td>
</tr>
<tr>
<td>2 parallel wire-electrodes 10cm apart (Configuration D)</td>
<td>4</td>
<td>28.49±15.05</td>
<td>3.82±0.01</td>
<td>3.82±0.01</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>25.86±5.32</td>
<td>4.05±0.03</td>
<td>3.19±0.14</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>27.81±6.15</td>
<td>3.94±0.15</td>
<td>2.95±0.01</td>
<td>18</td>
</tr>
</tbody>
</table>

As shown in figure 4 (d), the 2 wires 10cm apart at a height of 8cm reached a maximum $H_i/H_o$ of $3.94 \pm 0.15$, above $H_i/H_o$ at the transition point of $2.95\pm0.01$ in Table 2. However, an addition 8 kV beyond the transition point was required to reach the maximum $H_i/H_o$ value. As shown in Figure 4 and Table 2, the greatest values of $H_i/H_o$ occurs when only a single wire is above the hot plate. In all trials, the maximum $H_i/H_o$ was limited by the current safety limit of 300 mA. Finally, the heat transfer coefficient ratio would increase by approximately 55% before the transition point, but only an average of 11% after the transition point.

Figure 5 shows three plots of $H_i/H_o$ versus high voltage. Each plot represents a constant height of 4 cm (a), 6 cm (b), and 8 cm (c) with separate sets of points representing a different wire configuration. In figure 5(c), the 8 kV and 10 kV trials did not overcome the dielectric strength of the air, thus resulting in a negligible increase in the heat transfer coefficient ratio. The maximum $H_i/H_o$ of $5.45 \pm 0.16$ occurred with one wire at a height of 6cm (Figure 4 (a) and Figure 5(b)). However, as shown in figures 4(a) and 5(a), a single wire at a height of 4 cm had the greatest increase in the heat transfer coefficient ratio with a corresponding increase in voltage.
Figure 5: (a, b, c) Plots of the heat transfer coefficient ratio at a height of 4cm from the hot plate (a), at a height of 6cm (b), and at a height of 8cm (c). The blue circles represent trials with one wire. The yellow pentagons, green triangles, and red squares each represent trials with two electrodes, separated by 2cm, 6cm, and 10cm respectively from each other.

The greatest heat transfer coefficient ratio in a two-wire configuration of 5.10 ± 0.00 occurred when the electrodes are 6 cm apart from each other (figure 5 (b) and table 2). As shown in Table 2, the greatest heat transfer coefficient ratio at the transition point for trials with two electrodes was also at a 6cm electrode separation. As shown in figure 5, the single electrode configuration experienced the greatest changes in $H_i/H_o$ as wire height increased. The 2cm separation trial produced greater $H_i/H_o$ values than the 6cm separation trial until the transition point was reached. At a height of 4cm, the heat transfer coefficient ratio of two electrodes 2cm apart were on average 11% less than the single electrode trials. In wire heights of 6cm and 8cm of the same configuration, an average percent difference of 13% and 39% can be seen compared to a single electrode. Thus, when compared to each other, a two-electrode wire configuration was always inferior to a single electrode in terms of the heat transfer coefficient ratio for 8kV to 26kV.

As shown in figure 5 (a), (b), and (c), the same specific $H_i/H_o$ could be achieved utilizing different electrode configurations and voltages. Specifically, at an electrode height of 4 cm and a voltage of 16 kV, the two wire configurations of 2 cm and 6 cm electrode separation had similar $H_i/H_o$ values. In addition, in the 8cm wire height and 16 kV trials, the 2 cm and 6 cm separations also had similar $H_i/H_o$ values. This result was expected to be related to the relative humidity of the air, the applied voltage to the electrode, and the electrode height. An increase of humidity would cause a decrease in dielectric strength, thus reducing resistivity of the air and reducing the voltage required to cause EHD convection. However, the greatest range in the relative humidity of 28.49 ± 15.05% during the two-wire electrodes 10cm apart at 4cm height only caused $H_i/H_o$ to vary by ± 0.01 for the maximum value and at the transition point ± 0.01 in the two trials taken at that height. Similar results can be seen in the other configurations of Table 2, in that the humidity range did not cause a large variance in the heat transfer coefficient ratio. Thus, for individual trials compared to each other, the relative humidity did not seem to be a significant factor in affecting the heat transfer coefficient ratio.

The relative humidity may have affected the $H_i/H_o$ ratio for different electrode heights. In the two wire configurations of 4 cm electrode heights, the 6 cm electrode separation had the highest
humidity and highest $H_i/H_o$ value. However, in the 6 cm and 8 cm height trials of the same configurations, the 6 cm electrode separation had the highest $H_i/H_o$ while the 10 cm electrode separation had the greatest relative humidity. Thus, humidity may have impacted the $H_i/H_o$ ratio for comparing the 4 cm and 6 cm height trials, resulting in the 6 cm electrode separation trials to have a greater heat transfer coefficient ratio than the 2 cm electrode separation trials.

These results correspond with other research in the EHD field. Specifically, they are consistent with another study by Ahmedou et al. [4], which calculated a ratio of Nusselt number instead of the heat transfer coefficient with and without EHD enhancement in a channel. In the multiple wire configurations of the study by Ahmedou et al., it was concluded that decreasing interelectrode distance would increase the effect of EHD convection. This result of decreasing interelectrode distance is comparable to this study when comparing the 2 cm and 10 cm electrode separation configurations. In addition, it is expected that the humidity difference between configurations in the open system caused the 6 cm separation trial to have the greatest heat transfer ratio for two wire configurations. The study by Ahmedou et al. also showed that specific benefits towards EHD could be achieved by changing the wire configuration, height, or applied voltage. Finally, that the EHD enhancement is negligible for low ranges of voltages and large interelectrode separations [4]. The study also corresponded with a study by Bardy et al. [3], where a single wire electrode produced the greatest improvement to an initial drying rate.

**Conclusions**

This study focused on the increase to the free convection heat transfer coefficient using EHD convection. The data collected shows that a single wire electrode provides a greater benefit towards the heat transfer than two wire electrodes. Likewise, the increase towards the heat transfer coefficient decreases as voltage increases, this suggests that a cost verses benefit evaluation is necessary to select an optimum electrode configuration and voltage. It was found that the relative humidity may have impacted the $H_i/H_o$ ratio for the two wire electrode trials, resulting in a greater heat transfer coefficient ratio for configurations with higher humidity. Finally, specific heat transfer coefficients could be achieved using different wire configurations suggesting that an optimum configuration could be found to achieve a desired heat transfer coefficient.
**Index of variables**

\( R_p = \) Electrical resistance of plate (Ω)

\( V_p = \) Voltage applied to plate (V)

\( P_p = \) Power dissipated in the plate (W)

\( S_p = \) Surface area of plate (m²)

\( l = \) Thickness of plate (m)

\( \Phi_t = \) Total heat flux of plate (W/m²)

\( \Phi_{conv} = \) Heat flux due to convection (W/m²)

\( \Phi_{cond} = \) Heat flux due to conduction (W/m²)

\( \Phi_{rad} = \) Heat flux due to radiation (W/m²)

\( T_s = \) Surface temperature of (K)

\( T_a = \) Ambient temperature of (K)

\( T_w = \) Temperature of walls in room (K)

\( T_{top} = \) Temperature between plate and polystyrene (K)

\( T_{bot} = \) Temperature on the bottom of polystyrene plate (K)

\( h = \) Heat transfer coefficient (W m²/K)

\( \sigma = \) Stefan-Boltzmann Constant (5.68e-8 W/m² K⁴)

\( \lambda = \) Thermal conductivity of polystyrene (W/m K)

\( \varepsilon = \) Emissivity of the plate surface (≈1)
References


