Drying of Partially Wetted Materials with Corona Wind and Auxiliary Heat

F. C. Lai and C. C. Wang
School of Aerospace and Mechanical Engineering
University of Oklahoma
phone: (1) 405-325-1748
e-mail: flai@ou.edu

***Abstract*—Earlier studies have shown that electric field in the form of corona wind is very effective in drying fully wetted material. The present study experimentally examines the effectiveness of corona wind in drying a partially wetted material. In addition, auxiliary heating provided by a thermofoil heater attached to the bottom surface of the sample container has been used as a possible means to maintain the effectiveness of corona wind. For the present study, the sample used is 6 mm glass bead. A fine copper wire charged with negative potential is used as the emitting electrode. The water level inside the glass beads is below the external surface and is maintained constant in each set of experiment. For each case, a companion experiment is carried out simultaneously under the same ambient conditions but without the application of electric field or auxiliary heat. The result of which is used as a basis in the evaluation of the drying enhancement. The results show that electric field although is effective in the enhancement of drying rate of partially wetted glass beads, its effectiveness is gradually diminishing when water level in the glass beads recedes. By applying auxiliary heating, this shortcoming of EHD-enhanced drying can be overcome.**

I. INTRODUCTION

Earlier studies have shown that electric field can significantly enhance the drying rate of wet materials. It has been identified that the mechanism for this enhancement arises from the electrohydrodynamically (EHD) induced secondary flow when a high-intensity electric field is applied to ambient air. The EHD-induced secondary flow, which is also known as corona wind or ionic wind, can be thought of as a micro-jet of fluid issued from the charged electrode to the grounded surface. The net effect of this secondary flow is additional mixing of fluids and destabilization of boundary layer, therefore leading to a substantial increase in the mass transfer coefficients. Several studies have demonstrated the effectiveness of EHD drying. These include, for example, the drying of cookie dough [1], chopped onion [2], filter paper [2], wool [2], potato slab [3], apple slice [4], paper towel [5], and biomass materials [6]. As noted, this technique uses very small electric power as compared to those of conventional drying techniques. In addition, corona wind can be generated at room temperature and atmospheric pressure, which makes it particularly attractive for low temperature applications. Although corona wind has been proven effective in the early stage of drying when the material is fully wetted [7-9], its effectiveness for drying partially wetted materials has not been critically evaluated. For the present study, experiments have been carried out to evaluate the effectiveness of corona wind in the drying of partially wetted glass beads. In addition, auxiliary heating has been proposed as a backup option in case that the effect of corona wind does diminish when the water level in the material recedes. In this proposed scheme, auxiliary heating would drive moisture to the surface and corona wind could subsequently remove the moisture off the surface.

II. Experimental Setup and Procedure

A schematic diagram of the experimental setup for the present study is shown in Fig. 1. The main components are a small wind tunnel, a high voltage power supply, two digital balances, a temperature/humidity data logger, and one personal computer. Since the experimental setup is almost identical to that used by the authors in the previous studies [7-9], the description of the apparatus and experimental procedure is omitted here for brevity. The only difference in the experimental setup between the present and the previous studies is the addition of water level controllers. The water level controller is a Plexiglas box fitted with a movable Plexiglas tube. For the present setup, a reservoir is placed on top of a digital balance. A micro-pump is used to circulate water between the reservoir and the water level controller. Since the controller and the sample container are placed at the same level and they are connected to each other, water in the sample container can be maintained at any desired level by adjusting the height of the Plexiglas tube in the water

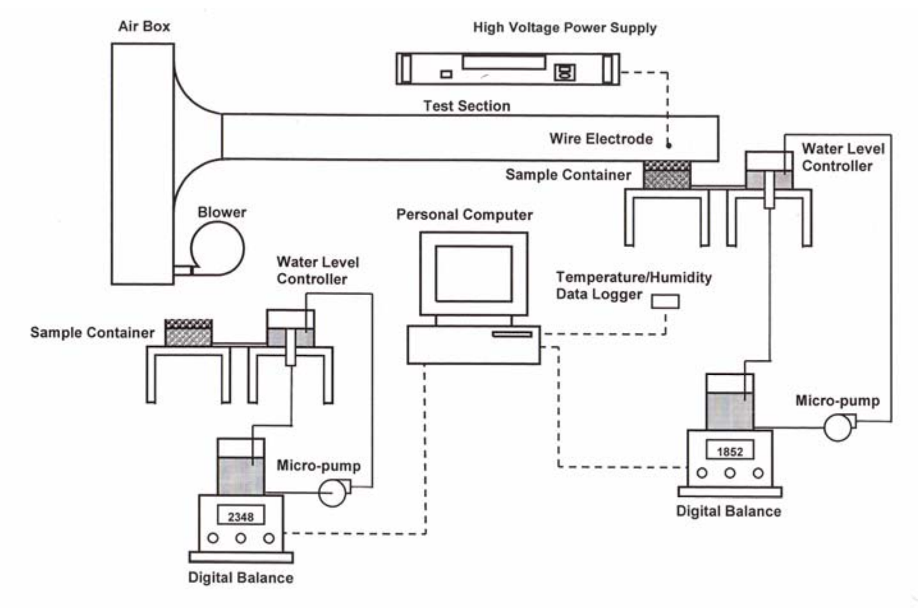

Fig. 1 Experimental Setup.

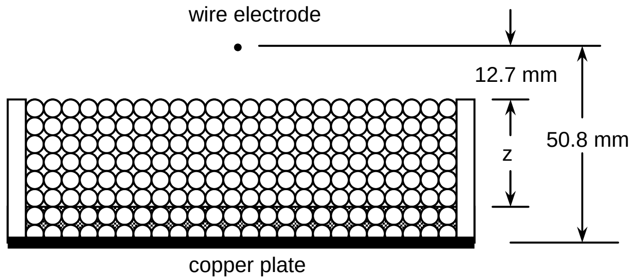

Fig. 2 Arrangement of wire electrode and water level.

level controller. Once the height of the Plexiglas tube is fixed, any excess water in the controller will flow over the tube and return to the reservoir.

For the present study, a copper wire with a diameter of 0.5 mm is the emitting electrode, which is suspended horizontally across the test section. The wire electrode is connected to a DC high voltage power supply and is charged with negative polarity. The distance between the electrode and sample surface is fixed at 1.27 cm (0.5 in.). The sample used is 6 mm glass beads which are gently packed into a sample container. The water level inside the container is maintained at a fixed height in each experiment with the aid of a water level controller. Two water levels are considered in the present study, z = 1.27 cm (0.5 in.) and 1.90 cm (0.75 in.) below the sample surface (Fig. 2). The sample container is grounded at the same level as that of the power supply. Auxiliary heating to the sample is provided through a thermofoil heater (MINCO-266) mounted on the underside of the copper plate of the sample container. A layer of insulation is placed underneath the copper plate to prevent heat loss and electric hazard. A DC power supply (HP E3614A) is used to power the thermofoil heater. It offers a maximum output power of 48 watts with voltage up to 8 volts and current up to 6 amps. The line regulation is less than 0.01% plus 2 mV and less than 0.01% plus 250 μA for any line voltage changed within the input rating for constant voltage and constant current, respectively.

Two experimental runs have been carried out simultaneously; one is conducted inside the test section and the other in the ambient. The latter is used as a reference in the evaluation of drying enhancement by electric field. Since both experiments have been run at the same time, the influence from the ambient condition on the results is expected to be the same. The drying enhancement by electric field alone was evaluated first, which was followed by the combined application of electric field and auxiliary heating. Two heating levels were considered, one was fixed at 3.3 W and the other 7.3 W. The average surface temperatures on the copper plate resulting from these two levels of heating were observed to be 26.8 ± 0.5 ºC and 34.0 ± 3.0 ºC, respectively. The actual plate temperature, which depended on the ambient temperature, deviated slightly from the average temperature indicated above. The applied voltage was increased from the corona threshold voltage until sparkover occurred. The drying rate was determined by the weight loss of water mass over time using a digital balance with a sampling rate of ten seconds. Each experiment was continued for at least five hours. Over the entire experiment period, it was observed that the change of ambient temperature was minimal since the lab was under well temperature control. However, the change in humidity in some cases was substantial, which may contribute to the scattering of data that are reported in the following discussion.

III. RESULTS AND DISCUSSION

To be consistent with the previous analysis [7-9], the present results are expressed in the dimensionless form for the ease of reference and comparison. In the absence of cross-flow, the enhanced drying rate by electric field can be expressed as function of the Sherwood number and EHD Reynolds number, which are defined below.

$$Sh = \frac{h_m d}{D} = \left[\frac{\dot{m}}{A_c \Delta c}\right]\frac{d}{D}, \tag{1}$$

$$Re_{EHD} = \frac{u_e d}{\nu} = \left[\sqrt{\frac{IL}{\rho b A_p}}\right]\frac{d}{\nu}, \tag{2}$$

where h_m is the mass transfer coefficient, which can be calculated from the data collected in experiments; D is the mass diffusivity of water vapor in dry air, which has been well documented in the literature [10]; and Δc ($= c_0 - c_\infty$) is the difference in water vapor concentration at the water level inside the sample and that in the ambient air. Their values can be calculated from the measured ambient temperature and relative humidity. In experiment, the corona wind velocity u_e is difficult to measure directly and accurately without a special instrument [11]. For the present study, its value is calculated based on the measured corona current as suggested from the previous work [12, 13]. Since the corona current increases with the applied voltage, it is clear that the EHD Reynolds number defined above also increases with the applied voltage. It has a value of zero when no electric field is applied.

The results of drying enhancement by electric field alone are presented in Fig. 3. As observed, when the water level is 12.7 mm below the sample surface, the drying enhancement by electric field (Sherwood number ratio) is a linear function of the EHD Reynolds number. But when the water level is further receded to 19.0 mm below the sample surface, the enhancement in drying rate by electric field becomes nonlinear. This behavior is similar to what has been reported by Alemrajabi and Lai [14]. Also observed for a small EHD Reynolds number ($Re_{EHD} < 35$), the drying enhancement by electric field is smaller when the water level inside the sample is lower. This indicates that corona wind cannot penetrate deeply enough to effectively remove the moisture trapped inside the sample. The applied voltage has to be sufficiently increased to show the corona wind effect. The maximum uncertainties for the Sherwood and EHD Reynolds numbers presented above were calculated to be 8% and 17%, respectively. The high uncertainty in the EHD number is mainly due to the measurements of corona current, particularly at voltages close to the threshold voltage. The data presented in Fig. 3 can be best correlated with the equations given blow. When presented in these forms, one observes that the Sherwood number ratio reduces to unity (i.e., natural drying) when there is no electric field (i.e., $Re_{EHD} = 0$).

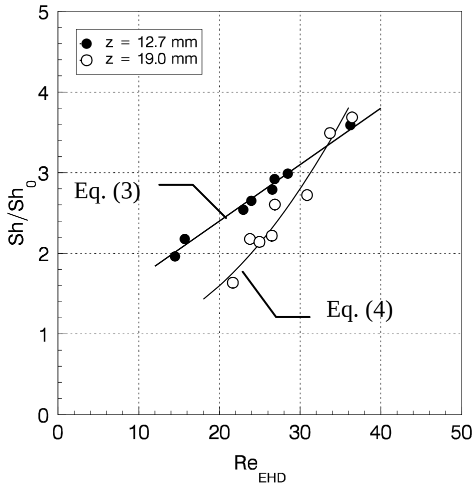

Fig. 3 Drying enhancement with the application of electric field only.

At z = 12.7 mm, $$\frac{Sh}{Sh_0} = 1 + 0.0826\,Re_{ehd} \qquad (3)$$

At z = 19.0 mm, $$\frac{Sh}{Sh_0} = 1 - 0.03\,Re_{EHD} + 0.003\,Re_{EHD}^2 \qquad (4)$$

The correlation coefficients for the above two equations are 0.97 and 0.94, respectively.

Since the effect of corona wind is diminishing when the water level inside the sample recedes, one may be able to overcome this deficiency by applying heat to the sample from below. It is speculated that the auxiliary heating may help drive moisture inside the sample to the surface by thermal buoyancy. Once moisture reaches the surface, corona wind can effectively remove it. Figure 4 shows the drying enhancement by the combined effects of corona wind and auxiliary heating for water level maintained at 12.7 mm below the surface. As expected, the drying enhancement does increase with the heating level. The heat added helps vaporize liquid water and drive the moisture to the surface while corona wind effectively removes it from the surface. For EHD-enhanced drying with auxiliary heating, the data are best correlated with the following form,

$$\frac{Sh}{Sh_0} = a + b\,Re_{EHD}\,. \qquad (5)$$

With auxiliary heating, the coefficient *a* will assume a value greater than unity because the auxiliary heating becomes the sole contributor to the drying enhancement when there is no electric field (i.e., $Re_{EHD} = 0$). A separate set of experiments were conducted to determine the sole contribution made by the auxiliary heating. It was found that drying rate was enhanced by 1.934 and 3.122 times of natural drying when heat was provided at 3.3 W and 7.3 W, respectively. The data presented in Fig. 4 can be correlated with the functional form shown in Eq. (5) and they are given by

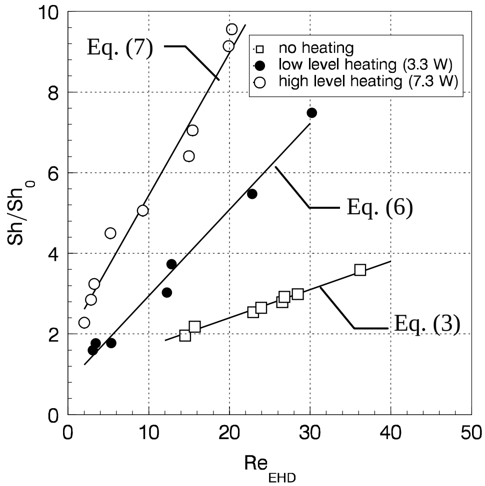

Fig. 4 Drying enhancement with the application of electric field and auxiliary heating (for water level at 12.7 mm below the sample surface).

For low level heating (3.3 W)
$$\frac{Sh}{Sh_0} = 0.804 + 0.214\,Re_{EHD}\,, \tag{6}$$

For high level heating (7.3 W)
$$\frac{Sh}{Sh_0} = 1.907 + 0.353\,Re_{EHD}\,. \tag{7}$$

The correlation coefficients for the above two equations are 0.99 and 0.97, respectively. From the above correlations, one notices that the drying enhancement by combined corona wind and auxiliary heating was actually less than that by the heating alone when the applied voltage was small. This may be due to the effect that the electric body force (which is responsible for the generation of corona wind) is acting against the thermal buoyancy (a result from auxiliary heating). When the applied voltage is small, the electric body force is too weak to disrupt the thermal buoyancy such that moisture cannot be effectively removed from the sample surface. It is believed that the interaction between corona wind and thermal buoyancy for the present case is similar to that reported in the previous study by Ngo and Lai [15]. The benefit of auxiliary heating can only be appreciated when the applied voltage is sufficiently increased (i.e., $Re_{EHD} > 5$).

For a lower water level (19.0 mm below the sample surface), the drying enhancement with the combined effects of corona wind and auxiliary heating is shown in Fig. 5. In this case, one observes that the data for drying enhancement scatter about an average value. For heating level at 3.3 W, the average drying enhancement is about 2.88 and is 2.69 for heating level at 7.3 W. It may first seem that the drying enhancement for the lower heating level is higher than that of the higher heating level. In fact, they are statistically the same when taking into consideration of experimental uncertainty involved. From Fig. 5, one can see that the combined effect of corona wind and auxiliary heating is

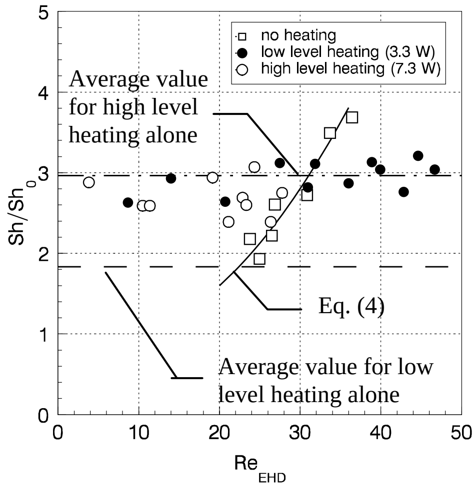

Fig. 5 Drying enhancement with the application of electric field and auxiliary heating (for
water level at 19.0 mm below the sample surface).

most beneficial when the heating level is low. For Re_{EHD} < 30, the drying enhancement by combined effect is greater than that by either one when acting alone. On the other hand, one observes that there is no significant difference in the drying enhancement between the use of combined effect and high level auxiliary heating alone. For Re_{EHD} < 30, the drying enhancement is mainly contributed by the heating alone, which implies that electric field in the form of corona wind has insignificant contribution to the drying enhancement when the auxiliary heating level is high. The contribution by electric field becomes noticeable only when the applied voltage is sufficiently increased (Re_{EHD} > 30).

The effectiveness of using corona wind and auxiliary heating in the drying enhancement can be evaluated from the performance factor shown in Fig. 6. The performance factor is defined here as the mass of moisture removed per energy input. Therefore, an efficient drying scheme should have a performance value as high as possible. From Fig. 6, one observes that EHD is a very efficient drying method for fully wetted materials. Its performance decreases when the applied voltage increases or the materials become partially dried. Although auxiliary heating is helpful in upkeep of the drying enhancement by corona wind, it is done at the expense of additional energy input. As such, its performance factor is very low as compared with that of EHD scheme alone. From Fig. 6, one clearly observes that EHD drying scheme can be more than ten times energy efficient than a thermal drying technique, particularly at a lower applied voltage.

IV. Conclusion

The drying enhancement of partially wetted glass beads by electric field has been experimentally evaluated in this study. The effects of corona wind and auxiliary heating on the drying rate have also been carefully examined. The results show that corona wind is

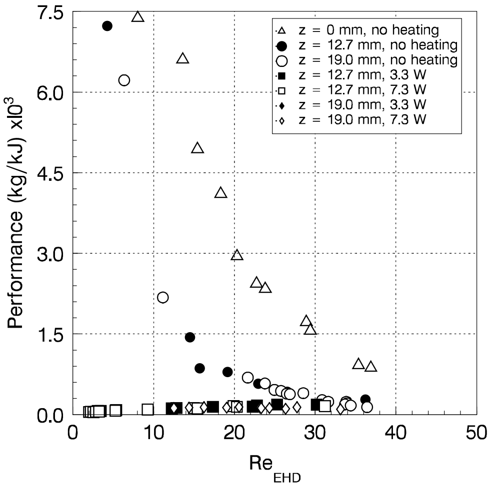

Fig. 6 Performance factor as a function of EHD Reynolds number.

most effective for fully wetted materials. Although it can also enhance the drying rate of partially wetted materials, its effectiveness gradually diminishes if moisture level in the material recedes further. The drying enhancement is shown to depend on the strength of the electric field (i.e., applied voltage) and water level in the sample. When the water level is high (1.27 cm from the surface or less), corona wind is still effective and its drying enhancement is a linear function of the applied voltage. However, when the water level is low (1.9 cm from the surface or greater), corona wind becomes less effective and its drying enhancement becomes a nonlinear function of the applied voltage. The reduction in the drying enhancement for partially wetted materials is common for all drying techniques and is not limited to EHD drying alone. With the application of auxiliary heating from the bottom of the sample, particularly at a lower level of heating (3.3 W), the drying enhancement can be sufficiently increased. But, no additional benefit is obtained if a higher level of auxiliary heating (7.3 W) is provided. In terms of energy usage, drying enhancement by electric field in the form of corona wind is proved to be an efficient scheme.

Although the present results show that the use of auxiliary heating can maintain the advantages of EHD drying, its efficiency in energy usage may not be as attractive as that of the corona wind alone. However, the results also show that the benefit of auxiliary heating can be obtained at a relatively low heating level. In fact, a higher heating level may actually produce adverse effect. For applications in industry, EHD technique can be used in the first stage of drying process when material is fully wetted. The heating part is secondary and is only used in the later stage of drying. EHD drying technique is even more attractive for applications where waste heat is available since waste heat can be recovered and put to good use. With the backup of auxiliary heating, EHD-enhanced drying will become a viable and attractive alternative to conventional techniques.

NOMENCLATURE

A_c surface area of sample that is exposed to corona wind, [m^2]
A_p surface area of the copper plate, [m^2]
b ion mobility of air, b = 2.1 x 10^{-4} $m^2/V\cdot s$ for negative corona discharge
c_0 water vapor concentration in air, [kg/m^3]
c_∞ water vapor concentration at the sample surface, [kg/m^3]
D mass diffusivity, [m^2/s]
d diameter of the wire electrode, [m]
h_m mass transfer coefficient, [m/s]
I corona current, [A]
$\dot{m}$ mass transfer rate, [kg/s]
s distance between the emitting electrode and ground surface, [m]
Sh Sherwood number as defined in Eq. (2)
Sh_0 Sherwood number for experiments conducted at ambient conditions
Re_{EHD} EHD Reynolds number as defined in Eq. (3)
u_e haracteristic ion velocity, $u_e = \sqrt{Is/\rho b A_p}$, [m/s]
ν kinematic viscosity of air, [m^2/s]
ρ density of air, [kg/m^3]

REFERENCES

[1] F. A. Kulacki and J. A. Daubenmier, “A Preliminary Study of Electrohydrodynamic Augmented Baking,” *Journal of Electrostatics*, vol. 5, pp. 325-336, 1978.
[2] A. Kirschvink-Kobayashi and J. L.Kirschvink, “Electrostatic Enhancement of Industrial Drying Process,” *Industrial & Engineering Chemistry Process Design and Development*, vol. 25, pp. 1027, 1986.
[3] Y. H. Chen and N. N. Barthakur, “Potato Slab Dehydration by Air Ions from Corona Discharge,” *International Journal of Biometeorology*, vol. 35, pp. 67-70, 1991.
[4] F. Hashinaga, T. R. Bajgai, S. Isobe and N. N. Barthakur, “EHD Drying of Apple Slices,” *Drying Technology*, vol. 17, pp. 479-495, 1999.
[5] H. R. Carlon and J. Latham, “Enhanced Drying Rates of Wetted Materials in Electric Fields,” *Journal of Atmospheric and Terrestrial Physics*, vol. 54, pp. 117-118, 1992.
[6] S. Banarjee and S. E. Law, “Electroosmotically Enhanced Drying of Biomass,” *IEEE Transaction on Industry Application*, vol. 34, pp. 992-999, 1998.
[7] F. C. Lai and K. W. Lai, “EHD-Enhanced Drying with Wire Electrode,” *Drying Technology*, vol. 20, pp. 1389-1401, 2002.
[8] F. C. Lai and D. S. Wong, “EHD-Enhanced Drying with Needle Electrode,” *Drying Technology*, vol. 20, pp. 1389-1401, 2003.
[9] F. C. Lai and R. K. Sharma, “EHD-Enhanced Drying with Multiple Needle Electrode,” *Journal of Electrostatics*, vol. 63, pp. 223-237, 2005.
[10] R. E. Bolz and G. L. Tuve, ed., *Handbook of Tables for Applied Engineering Science*, 2nd ed., Boca Raton, FL: CRC Press, 1973.
[11] D. W. Lamb and G. A. Woolsey, “Characterization and Use of an Optical-Fiber Interferometer for Measurement of the Electric Wind,” *Applied Optics*, vol. 34, pp. 1608-1616, 1995.
[12] J. H. Davidson and E. J. Shaughnessy, “Turbulence Generation by Electric Body Force,” *Experiments in Fluids*, vol. 4, pp. 17-26, 1986.
[13] F. C. Lai, P. J.Mckinney and J. H. Davidson, “Oscillatory Electrohydrodynamic Gas Flows,” *Journal of Fluids Engineering*, vol. 117, pp. 491-497, 1995.
[14] A. Alemrajabi and F. C. Lai, “EHD-Enhanced Drying of Partially Wetted Glass Beads,” *Drying Technology*, vol. 233, pp. 597-609, 2005.
[15] C. C. Ngo and F. C. Lai, “Effects of Electric Field on Natural Convection in an Enclosure Heated from Below,” *Proceedings of the 2001 National Heat Transfer Conference* (NHTC2001-20200, CD-ROM) , 2001.