Influence of Electrohydrodymics (EHD) on Heat and Mass Transfer in Unsaturated Porous Media

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Abstract

This study is to experimentally investigate the heat and mass transfer mechanisms in packed bed which composed of glass beads, water and air, for convective drying with electrohydrodynamics (EHD). Influences of a hot air temperature (~ 60°C) associated with various electric fields (0, 10, and 15 kV) on the temperature of packed bed at the different depths (0, 2, and 4 cm from the surface of packed bed) are investigated. Glass beads of 0.125 and 0.38 mm in diameters are used. The results show that with influence of corona wind on flow, drying rate is enhanced considerably. In addition, increasing the electrohydrodynamics dramatically reduces the moisture content in packed bed. Moreover, the electric field affects the temperature of packed bed layers nearby the surface. With higher the capillary pressure, the 0.125 mm glass bead provides moisture evaporation rate larger than the 0.38 mm glass bead.

Keywords: Electrohydrodynamics (EHD), Drying process, Porous media

1. Introduction

The drying process of porous media is a rather complicated process as coupled heat and mass transport phenomena are involved simultaneously. Conventional drying techniques usually use a hot airflow or thermal radiation from radiant heaters. As only a fraction of the input energy is absorbed by the material to be dried, these techniques usually have high energy consumption with a low efficiency. Particular in the food sector drying processes consume up to 10% of the total energy. Therefore, new techniques have to be investigated to make the drying processes more efficient. One way to improve the overall drying kinetics is to apply an electric field.

Electrohydrodynamic (EHD) drying uses a secondary bulk flow which is known as corona wind or ionic wind. By applying high voltage to an electrode, ions are produced by the ionization of gas in a high electric field. As shown in Fig. 1, these ions migrate to the electrode plate along electric field lines and collide with air molecules which then form the secondary bulk flow. As a result, the momentum transfer of gas is enhanced.

In the last decades, many researches, e.g., [2, 3, 4, 5, 6, 7], have been much paid attention on the enhancement of heat and mass transfer in drying processes. Lai and Lai [4] examined the influence of electric field parameters on the drying rate in a packed bed. A copper wire and a plate were located above and under the packed bed. It was
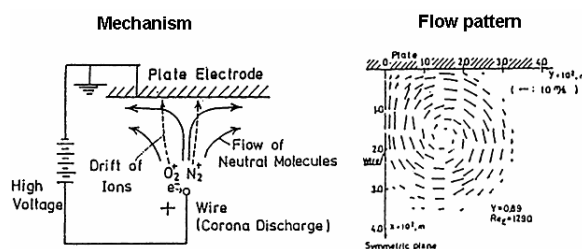

Fig. 1 Mechanism of Corona wind [1].

found that drying rate depended on the strength of the electric field and the velocity of the cross flow. With absence of cross-flow, the enhancement in drying rate increased linearly with the applied voltage. In addition, the influence of corona wind was suppressed by the increase of cross-flow velocity.

Alem-Rajabai and Lai [5] experimentally investigated the drying rate from partially wetted glass bead by electric field. In their experiments, a wire electrode and a copper plate were put above and under a packed bed, respectively. The results showed that EHD drying was most effective at the surface of the packed bed. In addition, the rate of increase in the drying

enhancement for positive corona was generally greater than that of negative corona.

Ratanadecho et al. [6] experimentally and numerically studied the microwave drying in unsaturated material with different porosities. This research was focused on the influence of moisture content on the mechanisms of vapour diffusion and capillary flow during microwave drying process in the packed bed. They found that small bead size led to much higher capillary forces and provided faster a drying time than a big bead size.

From above literatures, only the research done by Ratanadecho et al. [6] have studied the mechanisms of enhancement of the heat and mass transfer in the packed bed. However, due to behaviour of microwave heating, the heat is generated from the inside of packed bed. The objectives of this study are to investigate the influence of EHD on heat and mass transfer in a packed bed. In addition, the temperatures at three different positions from surface of the packed bed are examined.

2. Experimental setup and procedure

Schematic diagram of experimental setup is shown in Fig. 2. The rig is an open system. The wind tunnel is open on one side and hot air is blown into the ambient. Air is supplied from a blower and temperature of air is increased by a hot air generator which is connected to the rig. In order to control the air temperature, thermocouple sensor (TC) is put in front of the test section, which has the dimensions of 15×15 cm^2. The high voltage power supply is used to induce an electrical field in the test section. As shown in Fig.2, electrode wires are composed discharge and ground electrodes. The discharge electrodes are composed of 4 copper wires suspended from the top wall and placed in front of packed bed. Size of copper wires is 0.25 mm in diameter and the distance between the wires is 26 mm. Ground electrode is also made of copper wire, but suspended horizontally across the test section as shown in Fig. 3.

The porous packed bed used in this study is composed of glass beads, water and air. The container of glass beads is made from acrylic plate with a thickness of 0.5 mm. In addition, the dimensions are 4 cm wide, 12 cm long and 6 cm high. In order to investigate the heat transfer from hot air to the packed bed, three fiberoptic wires (LUXTRON Fluroptic Thermometer, Model 790, Santa Clara, Canada, accurate to $\pm 0.5^{O}$C) are placed in the middle point of the planes of 0, 2, and 4 cm, which are measured from the surface of the packed bed, as shown in Fig. 3.

In experiments, the maximum electric voltage is tested that breakdown voltage does not occur. The diameters of glass beads are 0.125 and 0.38 mm. The details of testing conditions and characteristics of water

transport in porous media are shown in Table 1 and 2, respectively.
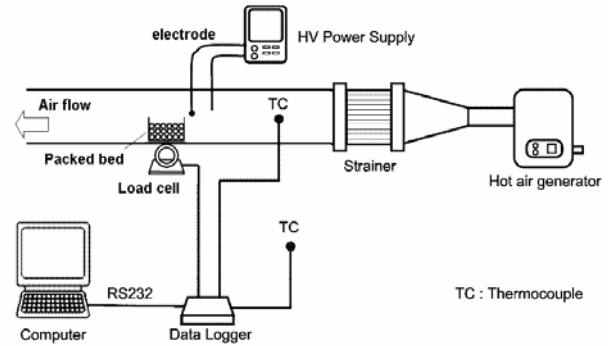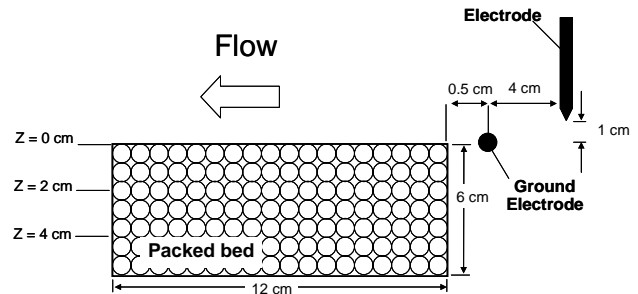

Fig. 2 Schematic diagram of experimental setup.

Fig. 3 Dimensions of packed bed and positions of electrode wires.

Condition	Symbol	Value
Initial moisture	M_{in}	22 %db
Drying temperature	T	50 – 60 ^{O}C
Ambient temperature	T_M	25 ^{O}C
Mean air velocity	U_b	0.35 m/s
Applied voltage	V	0, 10, 15 kV
Drying time	t	~ 48 hr
Glass beads	d	0.125, 0.38 mm

Table 1. Drying conditions.

Diameter, d (mm)	Porosity, ϕ	Permeability, K (m^2)
0.125	~ 0.385	~ 8.41×10^{-12}
0.38	~ 0.371	~ 3.52×10^{-11}

Table 2. Characteristics of water transport in porous media.

3. Results and discussions

In measuring the temperature in the packed bed, it is assumed that temperature is in state of thermodynamic equilibrium, thus temperatures of all phases, i.e., solid, liquid, and gas, are same. The average temperature of hot

air, which is measured behind packed bed, approximately is 55°C. Reynolds number, (Re = $\rho U_b D_h/\mu$, where ρ is density of air, μ is viscosity of air, and D_h is hydraulic diameter) of air flow is 3049.

Influence of drying with hot air on temperatures in packed bed

When electric current is not applied, drying process in the packed beds is controlled by the heat convection from hot air. Figure 4 shows that during first two hours, temperatures at all positions rapidly increase and are not much different. Then they still have same temperature until at 25 hr. This is because influences of capillary pressure on water saturation and heat from hot air transfer mainly subject to the moisture. Thus during first two hours, the moisture at the packed bed surface is evaporated with a constant drying rate. Afterwards, the capillary pressure, which is the function of pressure of liquid and pressure of gas in packed bed (i.e., $p_c = p_g - p_l$ [6]), becomes smaller but with influence of vapor diffusion, moisture within the packed bed is removed to the surface.

After 24 hours, temperature at each position gradually increases and tends to reach a constant temperature. In addition, the temperature at the surface (z = 0 cm) is the highest. This is natural because the amounts of moisture within packed bed content much decrease and glass beads near surface of packed bed become fully dry. Therefore, conduction heat transfer occurs near the surface and most of heat transfer is absorbed by glass beads. Moreover, the packed bed surface reaches thermal equilibrium.

From Fig. 4 – 6, temperature on the surface is not higher than the hot air temperature, which is measured behind the packed bed. It may be implied that for our case, the effect of joule-heating from electrode wire does not much influence on the temperature within packed bed.

Influence of drying with hot air and EHD on temperatures in packed bed

Clearly, when electric voltages are applied, as shown in Fig. 5 and 6, the constant–rate drying becomes much shorter, i.e., higher drying rate. This is because influence of corona wind, which is conducted by electric field, enhances the heat and mass transfer between hot air and surface on packed bed [7]. Then this causes the thermal boundary on surface of paced bed to be instability. Consequently, convective heat transfer coefficient is enhanced and then the temperature at the surface with EHD is higher than that of without EHD, as shown in Figs. 7 and 8.
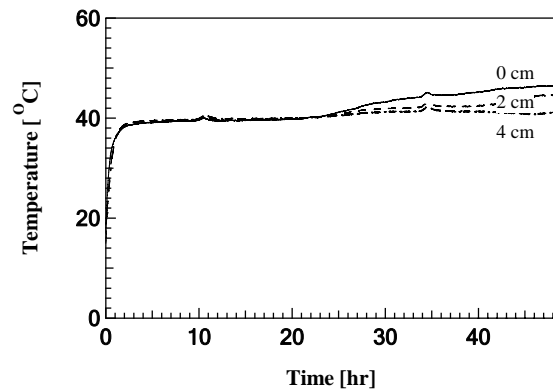

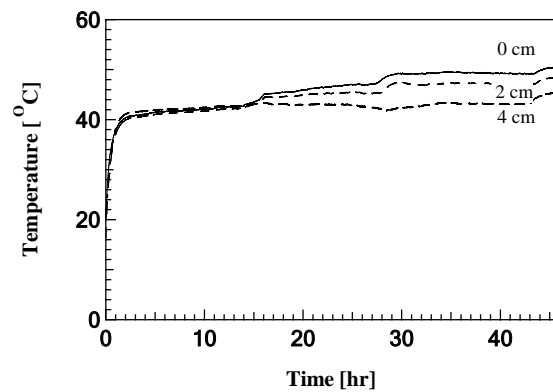Fig. 4 Temperature of packed bed with 0.38-mm bead in various depths when V = 0 kV.

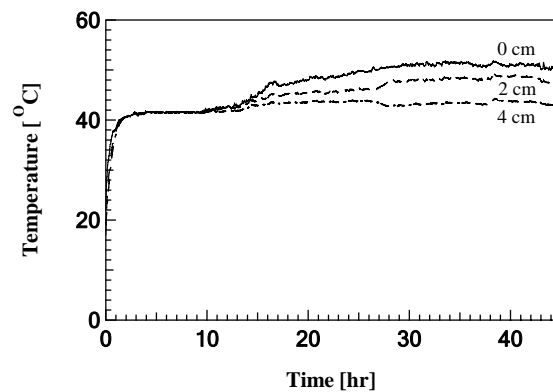Fig. 5 Temperature of packed bed with 0.38-mm bead in various depths when V = 10 kV.

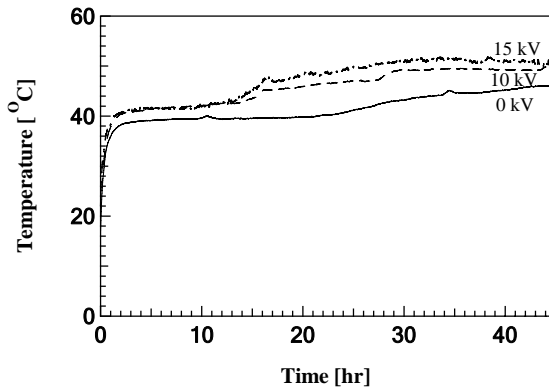Fig. 6 Temperature of packed bed with 0.38-mm bead in various depths when V = 15 kV.

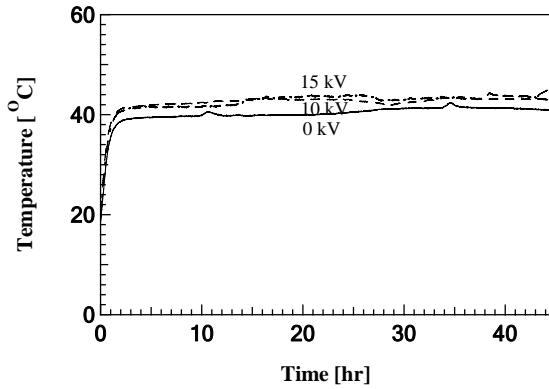Fig. 7 Temperature of packed bed with 0.38-mm bead in various voltages at z = 0 cm.

Fig. 8 Temperature of packed bed with 0.38-mm bead in various voltages at z = 4 cm.

Influence of bead sizes on temperatures

Figure 9 and 10 show the comparison on temperature at the surface (z = 0 cm) of packed bed between glass beads of 0.125 and 0.38 mm in diameter. When the electric voltage is not applied, smaller bead reaches a dry bulb temperature faster than bigger one. This is because influence of capillary pressure in smaller bead (with higher porosity) is higher than that in bigger bead (with smaller porosity), as shown in Fig. 10.
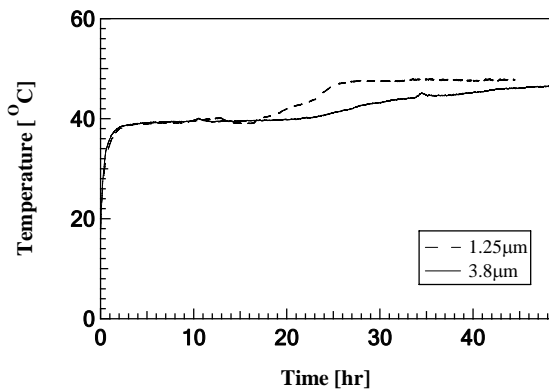

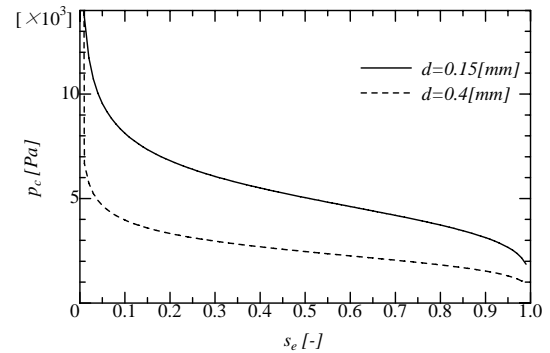Fig. 9 Comparison on temperature at z = 0 cm between beads of 0.125 and 0.38 mm when V = 0 kV.

Fig. 10 Typical relationship between capillary pressures, p_c, and effective water saturation, s_e [6].

Influence of bead sizes on moisture content

Figure 11 shows the comparison on weight loss of water in packed bed with different bead sizes when electric voltage is 15 kV. During first seven hours, the rates of weight losses of water of two beads seem not much different. This is because moisture content within both packed beds is still high. However, due to the influence of capillary pressure, moisture removed to the surface of packed bed of 0.125-mm bead is higher than that of 0.38-mm bead. After a certain time, a large amount of moisture on the surface of packed bed of 0.125 mm evaporated to hot air. Thus the constant-rate drying period of smaller bead size is longer than that of bigger one. In the other words, drying time of smaller beads is shorter than that of bigger beads.
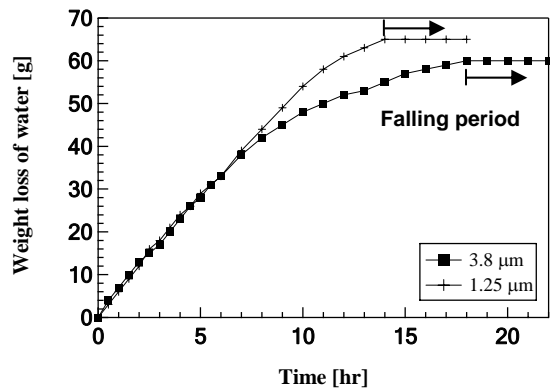

Fig. 11 Comparison on weight loss of water in packed bed between beads of 0.125 and 0.38 mm when V = 15 kV.

Moreover, by comparing Fig. 6 and Fig. 11, it is shown that for the case of beads of 0.38 mm, the constant–rate drying period is influenced by two mechanisms, i.e., capillary pressure effect in the first two

hours, and water evaporation during 2 – 18 hours later. After 18 hours, the influence of capillary pressure much decreases, and the weight loss of water tends to be constant. As mentioned before, this falling period is under the influence of vapor diffusion.

4. Conclusions

Influence of hot air with/without electric field on the heat and mass transfer in a porous packed bed is experimentally investigated through measurement of temperature at three different positions and of weight loss of water in packed bed. In addition, results of two different bead sizes (i.e., 0.125 and 0.38 mm in diameter) are compared.

With influence of corona wind, which is generated from four electrode needles, the heat transfer coefficient above packed bed is increased. Thus temperatures in packed bed are increased. In addition, each temperature tends to reach a constant value faster than when electric field is not applied. Moreover, with higher voltage applied heat from hot air much transfers into packed bed.

By comparing the sizes of glass beads in packed beads, due to higher capillary pressure, the smaller beads tend to give a constant weight loss of water faster than that of bigger beads. In the other word, time drying of smaller beads is shorter.

To more understand the phenomena of drying process, we will numerically study the relationships among various parameters in porous packed bed.

5. Acknowledgement

6. References
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