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Enhancement of Mass and Heat Transfer in the Unsaturated Double-layer Packed-bed with Electric fields

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Abstract

The enhancement of mass and heat transfer by electric fields, so-called electrohydrodynamics (EHD), has been experimentally evaluated in this study. Influences of hot-air flow with and without electric fields on the water moisture content and temperature in the unsaturated double-layered packed bed are examined. Velocity of air flow is about 0.33 m/s. Electric fields are applied in the range of 0 – 15 kV. Glass beads of 0.125 and 0.38 mm in diameters are employed. Enhancement of heat and mass transfer is revealed through measuring the temperatures and weight loss of moisture content of the packed beds. The results show that with influence of corona wind on flow above the packed bed, the drying rate is enhanced considerably. Due to the effect of capillary pressure difference, increase of temperatures in double-layer packed bed appears unlikely that in single-layered packed bed. By comparing without electric field cases, the drying rate of double-layered packed bed cases are increased by 1.5 – 1.97 times. In addition, the drying rate of fine-coarse packed-bed cases are 3.13 – 3.67 higher than that of coarse-fine pack-bed cases.

Keywords: Electrohydrodynamics, Drying, Heat and mass transfer.

1. Introduction

Drying of porous material is a separation process in solid-liquid system, and plays an important role for many research fields, such as chemical, pharmaceuticals, agriculture. With occurring simultaneously transient transfer of heat and mass, drying is one of complicated phenomena, and is not clearly understood.

Due to simple construction, conventional drying method with hot-air flow is commonly used for removing the moisture content from agriculture products. By this method, however, drying period is long, resulting in large energy consumption.

Basically, the drying rate involves with two processes [1], i.e., the movement of moisture internally within the porous material, and the removal of water as vapor from the material surface. The movement of moisture in porous material depends on the external conditions of temperature, air humidity and flow, area of exposed surface, and pressure. In order to increase removing the moisture within the material, many researches [e.g., 2, 3, 4] have paid much attention on microwave heating in porous materials. Gori et al. [2] utilized the microwave to remove the moisture content within porous material. Theoretically, microwave irradiation penetrates in the bulk of the material, and thus creates a heat source at certain locations. This causes moisture inside material to heat, and moves moisture toward the material surface. In order to enhance the removal of water from the porous material surface, Chaktranond et al. [5] applied the electric fields on the hot-air flow, and investigated the drying rate of a single-layered porous media. It is found from the experimental results that the effect of the corona wind conducted by electric fields in flow can enhance the transfer of heat and mass on the material surface considerably. This is because the thickness of boundary layer on the material surface is accomplished to be thinner. Moreover, due to effect of capillary pressure, the drying rate of smaller bead size is higher than that of bigger bead size.

To get more understanding in the mechanisms of drying in complex geometry of porous material, this study aims to investigate the transfer of heat and mass within a double-layered porous packed bed (where a porosity size layer overlays the other porosity size layer) subjected to the influence of hot-air flow and electric fields. Transient temperature in the packed bed is measured at various locations, and the rate of drying is revealed through measurement of the gross weight loss of moisture content.

2. Principle of Electrohydrodynamics

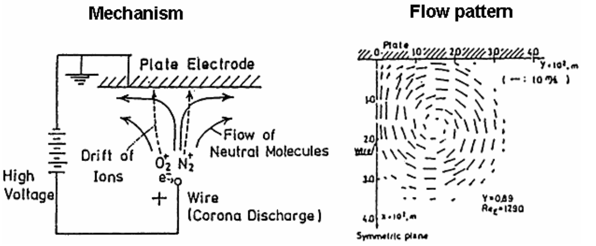

Fig. 1 Mechanism of corona wind [6].

Theoretically, electrohydrodynamic forces (EHD) generates the 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.

Idea of heat-and-mass transfer enhancement with utilizing EHD is shown in Fig. 2. When hot-air flow exposed to electric fields, the flow is circulated, and then this circulating wind will reduces the influence of boundary layer on the packed-bed surface. This causes moisture on surface to move much into the air flow, and heat to transfer much into the packed bed. Consequently, the rate of moisture removal is enhanced.

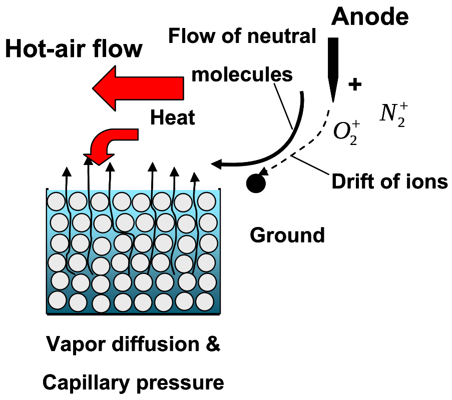

Figure 2. Idea of enhancement of heat and mass transfer with corona wind [5].

3. Experimental setup and procedure

Schematic diagram of experimental setup is shown in Fig. 3. 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. 4, 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. Diameter of each copper electrode is 0.25 mm and the spacing between each wire is 26 mm. Ground electrode is also made of copper wire, but suspended horizontally across the test section. The porous packed bed used in this study is composed of glass beads, water and air. The container of glass beads is made of acrylic plate with a thickness of 0.5 mm. In addition, the dimensions are 3.5 cm wide, 12 cm long and 6 cm high. Moreover, to control heat transfer from hot air towards only the upper surface of packed bed, other sides are insulated by rubber sheet. In order to investigate the heat transfer within the packed bed, three fiberoptic wires (LUXTRON Fluroptic Thermometer, Model 790, Santa Clara, Canada, accurate to ±0.5^{O}C) are placed in the middle point of the planes of 0, 2, 3 (interface plane), and 4 cm, which are measured from the surface of the packed bed.

Figure 5 shows the configuration of the double – layered packed beds, where fine bead layer overlaid coarse bead layer is of the F – C case, and the inverse is of the C – F case. Additionally, both layers have a same thickness.

In experiments, the maximum electrical voltage is tested that breakdown voltage does not occur. The diameters of glass beads are 0.125 mm for fine beads and 0.38 mm for coarse beads. The details of testing conditions and characteristics of water transport in porous media are shown in Table 1 and 2, respectively.

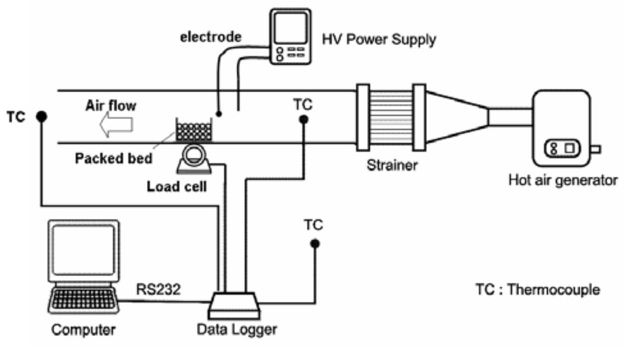

Figure. 3. Schematic diagram of experimental setup.

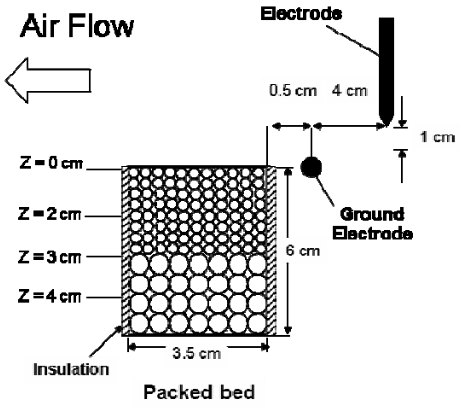

Figure 4. Dimensions of packed bed, locations of electrodes, and positions of temperature measurement.

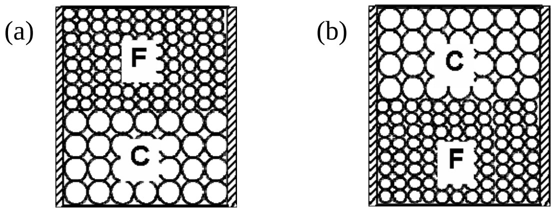

Figure 5. Configuration of double – layered packed bed: (a) F – C case, and (b) C – F case.

Table 1. Testing conditions

Condition	Symbol	Value
Initial moisture	$\chi_{db,i}$	22 %db
Drying temperature	T	50 – 60 ^{O}C
Ambient temperature	T_a	25 ^{O}C
Mean air velocity	U_b	0.33 m/s
Applied voltage	V	0, 10, 15 kV
Drying time	t	~ 24 hr
Glass beads	d	0.125, 0.38 mm

Table 2. Characteristics of water transport in porous media.

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}

4. Results and discussions

In the experiment, it is assumed that the temperature in the packed bed 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^{O}*C*. Bulk mean velocity of air flow is 0.33 *m/s*, which is equivalent to Reynolds number of 2,610.58 ($Re = \rho U_b D_h/\mu$, where ρ is density of air, μ is viscosity of air, and D_h is hydraulic diameter).

4.1 Flow visualization

In order to observe the motion of flow subjected to the electric fields, this study utilizes incense smoke technique. A spot light of 500 W is placed at the outlet of channel, and the light direction is opposite on the flow direction. Due to high speed of flow, the bulk mean velocity is reduced to 0.1 m/s. In addition, the motion of flow is continuously captured by a digital video camera recorder (SONY DCR-PC108/ PC109E).

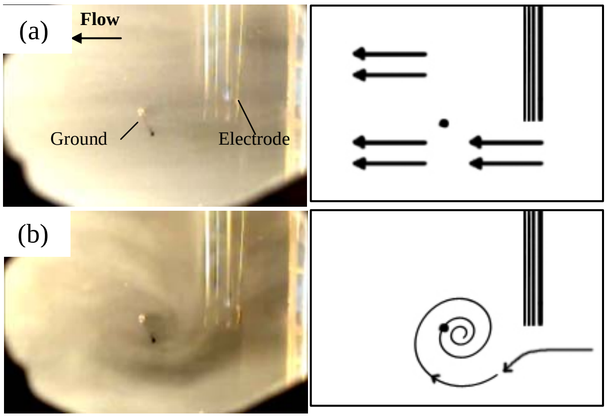

Figure 6. Motion of air flow: (a) without electric fields, and (b) with electric fields at V = 10 kV.

As shown in Fig. 6, under the influence of EHD, air flow neighboring electrodes is induced by electric fields, and is circulated around ground electrode. In addition, strength of vortex is proportional to the magnitude of electrical voltage applied.

4.2 Fine-coarse case

As shown in Fig. 7, when fine beads overlay coarse beads, in the early period (~ 1 hr), all temperatures in this packed bed rise up steadily. Later, they become constant, and temperature on surface of this packed bed is lowest. Until a certain time, the temperature on surface rapidly, and is higher than the other layers. This is because of the effect of capillary pressure difference. From experimental results of Chaktranonod et al. [5], small bead packed bed provides the capillary pressure (p_c) higher than bigger bead packed bed. In addition, the relationship between the capillary pressure and the water saturation is defined by using Leverett functions $J(s_e)$ [4, 7],

$$p_c = p_g - p_l = \frac{\sigma}{\sqrt{K/\phi}} J(s_e) \qquad (1),$$

where p_g and p_l are pressure of gas and liquid phases, respectively, S_e is the effective water saturation associated with the irreducible water saturation, and σ is surface tension.

From Eq. (1), if $(\sigma\ J(S_e))_{\text{fine}}$ ~ $(\sigma\ J(S_e))_{\text{coarse}}$ then $p_{c,\text{fine}} > p_{c,\text{coarse}}$. It means that in the case of same water saturation, a smaller particle size corresponds to a higher capillary pressure.

In the initial period, if both layers have same amount of saturation, then difference of capillary pressure will be happened. Therefore, effect of capillary action in the fine bead layer (upper layer) will induce the moisture from the coarse bead layer (lower layer) to its layer. This causes void in the lower layer to fill with more the vapor phase. Therefore, with a same heat flux, temperature of lower layer becomes high. As moisture evaporating process proceeds, temperatures of porous packed are constant, where heat is used for changing phase. Until a certain time, the surface becomes dry; heat will mainly transfer with conduction. Consequently, temperature in the upper layer rises up again when drying zone starts happening, and the temperature of surface layer is higher than the other layers.

It is evident in Fig. 8 that when electrical voltage supplied more increases, corona wind more influences on the boundary layer on the upper layer surface, and this causes heat and mass transfer between layers to be increased, resulting in higher temperature in each layer.

4.3 Coarse-fine case

Figure 9 shows temperatures results when coarse beads overlay fine beads. Unlike F-C case, without electric fields applied, the temperature on the surface layer is highest. While with electric fields applied, temperature on the surface becomes lowest in during early period. In addition, temperature is higher when electrical voltage higher increases. Even though when electrical voltages are applied, the C-F results exhibit likely F-C cases, temperatures in C-F cases still are low. This is because moisture in the coarse layer (upper layer) slowly transfers to the surface, and this effect retards the moisture transfer from the lower layer to the upper.

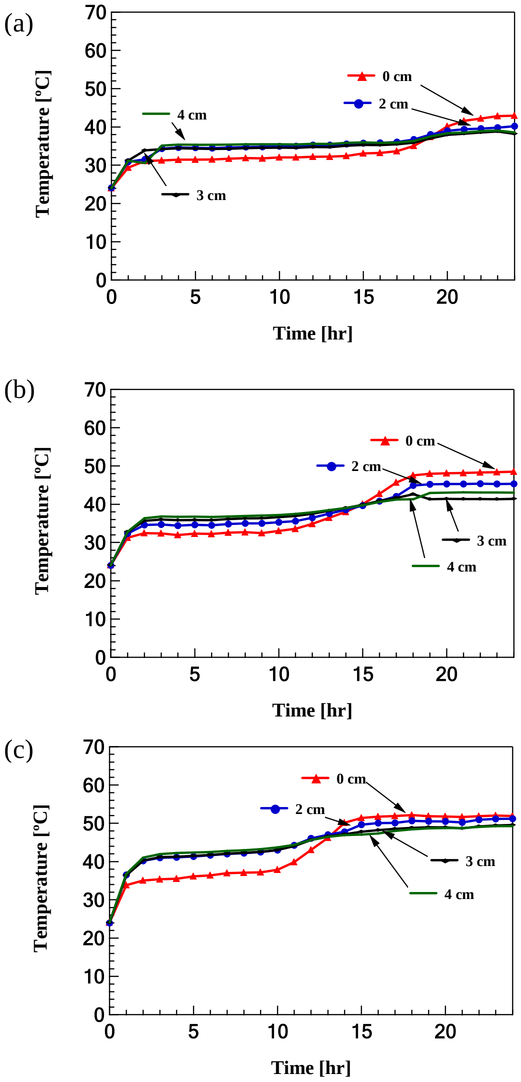

Figure 7. Temperature in F-C packed bed in various positions: (a) V = 0 kV, (b) V = 10 kV, and (c) V = 15 kV.

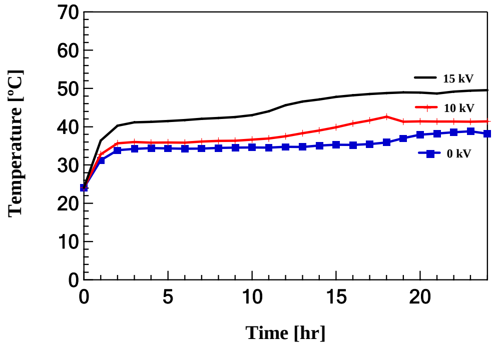

Figure 8. Temperature at z = 3 cm in F-C packed bed under various electric voltages.

Moisture in the fine layer (lower layer) congregates on the interface layer. Therefore, temperatures in both layers are low in this case.

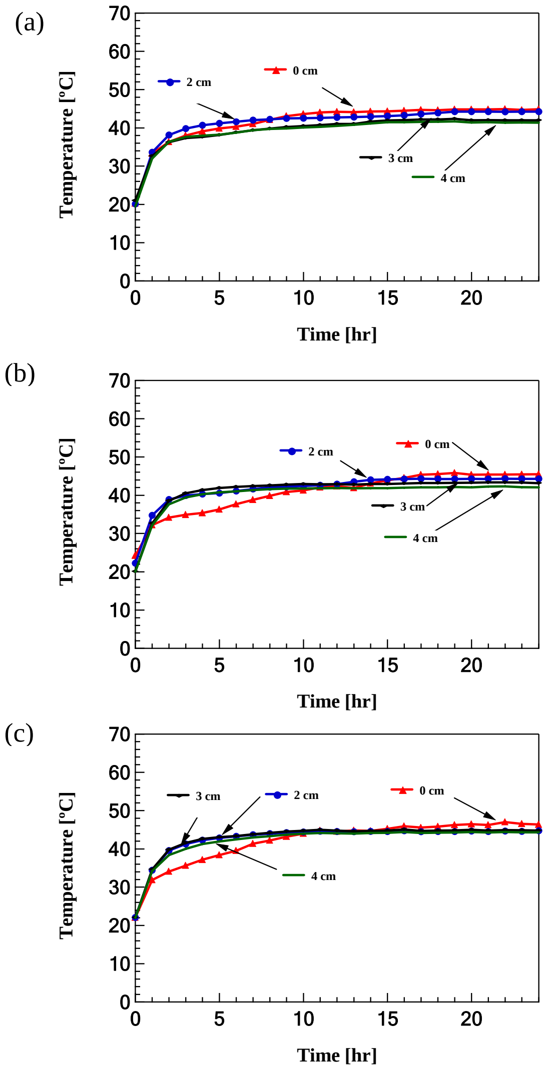

Figure 9. Temperature in F-C packed bed in various positions: (a) V = 0 kV, (b) V = 10 kV, and (c) V = 15 kV.

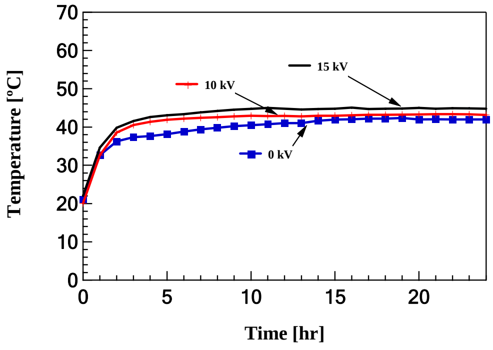

Figure 10. Temperature at z = 3 cm in F-C packed bed under various electric voltages.

4.4 Comparisons between F-C and C-F cases

Figure 11 shows the comparison on temperatures between F-C and C-F cases at different elevations, i.e., at the surface (z = 0 cm), and at the interface layer (z = 3 cm), when electrical voltage of V = 15 kV is applied. In the early period, heat transfers from hot air into both cases and increases their temperatures. Afterwards, heat is used for moisture evaporating process with constant temperature, i.e., latent heat. After the drying period, heat rises up temperatures of packed bed again, and this heat is a sensible heat form. Until thermal equilibrium, the temperature becomes constant again.

Due to effect of capillary pressure difference in F-C cases, moisture from the lower layer transfers to the upper layer faster. This causes, in the drying period, the temperatures on both elevations of F-C cases to be lower than that of C-F cases. After occurrence of drying on the surface, heat from hot-air flow is transferred to the structure of porous material. Therefore, temperature in F-C cases rapidly increases. In C-F cases, due to effect of low capillary pressure in the upper layer and high capillary pressure in lower layer, moisture transfer from the lower layers is retarded, resulting in low temperature.

It is clearly seen in Fig. 12 that the moisture removal in C-F case is much lower than that in F-C case. With influence of EHD, the drying rate can be increased. By comparing the rate of drying, F-C packed bed has 3.13 – 3.67 times higher than C-F packed bed. In addition, with electrical voltage applied, the drying rate is improved about 1.5 – 1.97 times.

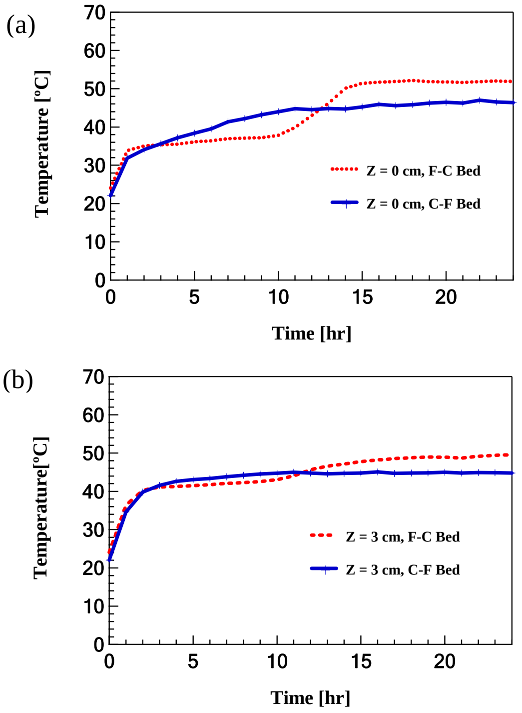

Figure 11. Comparison on temperature between F-C and C-F cases when V = 15 kV: (a) at z = 0 cm, and (b) at z = 3 cm.

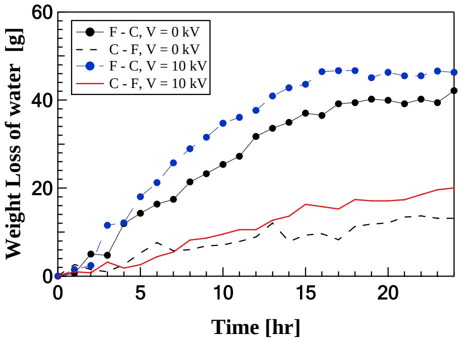

Figure 12. Comparison on weight loss of water in packed bed between F- C and C – F cases when V = 0 and 10 kV.

5. Conclusion

Influence of hot air with/without electric field on the heat and mass transfer in the double-layered porous packed beds is experimentally investigated through measurement of temperature at three different positions and of weight loss of water in packed bed. In addition, experimental results of fine beads overlay coarse beads (F-C cases) and of coarse beads overlay fine beads (C-F cases) are compared.

With influence of corona wind, which is generated from four electrode needles, the boundary layer on packed bed surface is reduced. Thus temperatures and drying rate of the packed beds are enhanced, and their increases depend on the magnitude of electrical voltage supplied.

Due to effect of capillary pressure difference, the lower layers of both cases have low temperature in the drying period with constant temperature. In addition, with retarding of moisture motions in the upper layer of C-F cases, moisture in the lower layer do not much move towards the upper layers, resulting in low temperature. While effects of capillary pressure difference in F-C cases conduct moisture in the lower layers towards the upper layers better.

With electrical voltage applied, the drying rate is improved about 1.5 – 1.97 times. In addition, the drying rate of Fine-Coarse packed-bed case is 3.13 – 3.67 higher than that of Coarse-Fine pack-bed case.

Acknowledgment

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