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Analysis of Heat and Mass Transfer in Unsaturated Porous Packed beds subjected to Electrohydrodynamics

(Effect of Electrical Voltage, Porosity, and Porous Structure)

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Abstract

This research aims to experimentally analyze the effect of electrical voltage, porosity, and porous structure on the heat and mass transfer in a convective drying of single- and double-layered packed beds composed of glass beads, water and air. The effects of drying time, electric field, particles size and the layered structure are examined. Glass beads of 0.125 and 0.38 mm in diameters are employed in the packed beds. Velocity of airflow is about 0.33 m/s and temperature of air is controlled at 60^{O}C. Electric fields are applied in the range of 0 - 15 kV. Enhancement of heat and mass transfer is revealed through measuring the temperature and weight loss of moisture content of the packed beds. The results show that with influence of Corona wind on flow above the packed beds, the drying rate is enhanced considerably. In addition, arrangement of the glass-bead-layered structure much influence on the temperature distribution and rate of moisture content in packed bed. Due to the effect of capillary pressure difference, increase of temperatures in double-layered packed bed appears unlikely that in the single layer. Moreover, in the double-layered cases, the drying rate of fine-coarse packed bed is higher than that of coarse-fine packed bed.

Keywords: Electrohydrodynamics, Drying process, Heat and mass transfer

1. Introduction

Drying is a process in which water in a porous medium is vaporized and subsequently removed it. Playing an important role in many applications, such as textile, chemical, pharmaceuticals, and agriculture, drying is one of most complicated phenomena encountered in engineering because of the simultaneous heat and mass transfer taking place during the process. In addition, it is not clearly understood.

In agricultural industries, drying method with hot-air flow is widely used for removing the moisture content from agriculture products. Drying period, however, is long, resulting in large energy consumption. In order to improve drying rate, many researchers have paid much attention in development of hot-air drying cooperating with the other methods, such as microwave, e.g. [1-3], infrared, e.g. [4, 5], and electric fields, e.g. [6]. In order to increase removing the moisture within material, microwave irradiation penetrates in the bulk of the material, and creates a heat source at a certain location. Infrared drying is suitable to dry thin layers of material with large surface exposed to radiation. Infrared radiation is transmitted through water at a short wavelength, while long wavelength, it is absorbed on the surface [7]. In order to enhance the removal of water from the porous material surface, Chaktranond et al. [6] applied the electric fields on the hot-air flow. It is found from the experimental results that the effect of the corona wind conducted by electric fields enhances the temperature and drying rate of porous packed bed considerably.

This research aims to study of the drying mechanisms and to analyze the heat and mass transfer in the single- and double-layer porous materials subjected to hot-air flow and electric fields.

2. Theory

2.1 Corona wind

Concept of improving hot – air drying efficiency with EHD is shown in Fig. 1. When high electrical voltage is applied, air flow charged induces the free air to circulate. Due to effect of circulating wind, moisture on material surface moves much to the hot – air flow and also heat can much transfer from hot air to the material. Consequently, the rates of moisture removal and heat transfer are enhanced.

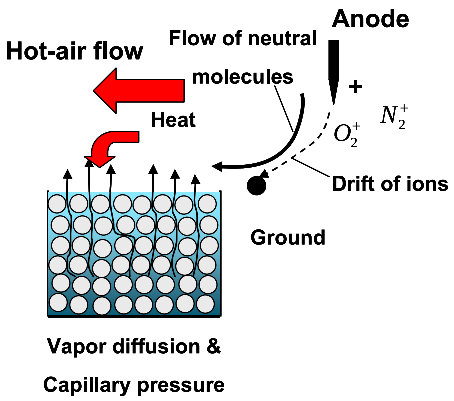

Fig. 1 Idea of enhancement of heat and mass transfer with corona wind [6].

2.2 Drying equations

Water saturation of a porous medium is defined as

$$S = \frac{Volume\ of\ \ fluid}{Total\ volume\ of\ voids} = \frac{V_{water}}{V_{void}} \qquad (1).$$

Moisture content in material is the ratio of total mass of water to total mass of dry solid, i.e.

$$X = \frac{M_{water}}{M_{solid}} \qquad (2).$$

Eq. (2) can be written in term of water saturation (S), and it is

$$X = \frac{\phi \rho_{water}}{(1-\phi)\,\rho_{solid}} S \qquad (3),$$

where ϕ is porosity and ρ is density.

From Fourier's law, heat flux through porous material is computed by

$$q = -\lambda_{eff} \nabla T \qquad (4),$$

where λ_{eff} is the effective thermal conductivity, and ∇T is temperature gradient in packed bed. In addition, it is assumed to be a function of water saturation, and is defined as [3]

$$\lambda_{eff} = \frac{0.8}{1+3.7e^{-5.95S}} \qquad (5).$$

Energy balance on packed bed surface exposed to air flow can be calculated by

$$-\lambda_{eff}\frac{\partial T}{\partial z}=h_c\left(T_s-T_{air}\right)+\dot{m}_{water}h_v \qquad (6),$$

where h_c is convective heat transfer coefficient, $\dot{m}_{water}$ is volumetric evaporation rate, h_v is latent heat of vaporization, T_s and T_{air} are temperature at surface and of air, respectively.

The relationship between the capillary pressure and the water saturation is defines by using Leverett functions $J\left(S_e\right)$ [2, 3],

$$p_c = p_{gas} - p_{liquid} = \frac{\sigma}{\sqrt{K/\phi}}J\left(S_e\right) \qquad (7),$$

where p_{gas} and p_{liquid} 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.

3. Experimental setup

Schematic diagram of experimental setup is shown in Fig. 2. Air is introduced into wind tunnel and heated by electric heater. To control temperature of hot air, thermocouple sensor (TC) is installed in front of the test section, which has the dimensions of 15 cm×15 cm. The high voltage power supply is used to induce an electrical field in the test section.

As shown in Fig. 3, electrode wires compose of copper discharge and ground electrodes. Four discharge electrodes are suspended from the top wall and are placed in the front of packed bed. In addition, a ground electrode is placed across the air flow. Dimensions of porous packed bed are 3.5 cm (W) × 12 cm (L) × 6 cm × (H), and inside composes of glass beads, water and air. To control heat transfer from hot air to packed bed, all sides are insulated by rubber sheet, except the upper side exposed to air. In order to measure the temperature of packed bed, three fiber optic wires (LUXTRON Fluroptic Thermometer, Model 790, Santa Clara, Canada, accurate to ±0.5$^{\mathrm{O}}$C) are placed at z = 0, 2, and 4 cm, which are measured from the surface of the packed bed.

Figure 4 shows the configuration of the double-layer packed beds. For the single-layer case, packed bed is filled with a glass bead size. While in the double layer case, packed bed is filled with two different sizes of glass bead. Hereafter, fine bead layer overlaid coarse bead layer is of the F–C case, and the inverse is of the C–F case. Additionally, the thickness of both layers is identical.

Testing conditions are shown in Table 1. Glass beads diameters are 0.125 mm and 0.38 mm for fine and coarse beads, respectively. In addition, characteristics of porous packed bed shown in Table 2.

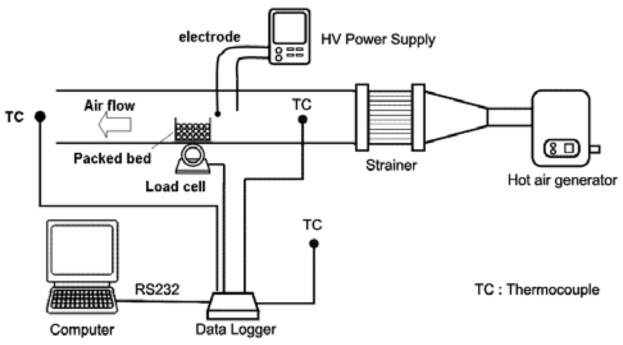

Fig. 2. Schematic diagram of experimental setup.

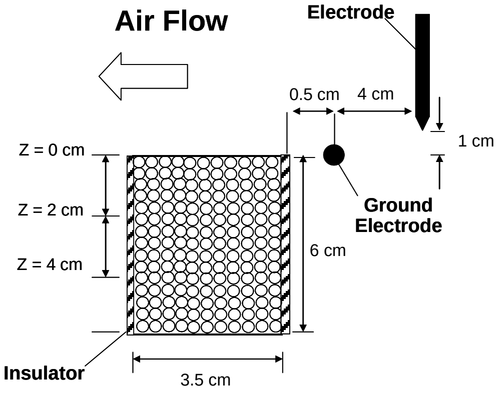

Fig. 3 Dimensions of packed bed, locations of

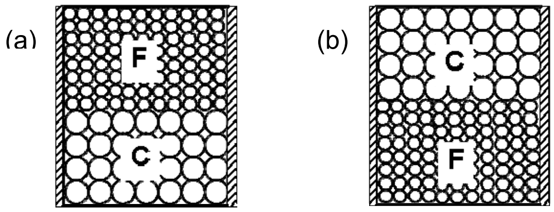

Fig. 4 Configuration of double-layer packed bed: (a) F – C case, and (b) C – F case.

Table 1 Testing conditions

Condition	Symbol	Value
Initial saturation	$S_{,int}$	50 – 100 %
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 - 48 hr

Table 2 Characteristics of porous media.

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

4. 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.

4.1 Single-layer packed bed

Figure 5 and 6 show influence of EHD on temperature in 0.125-mm-bead packed bed at z = 0 and 4 cm, respectively. Clearly, when electric fields are applied, the temperature rapidly increases. In addition, the temperature is higher with higher voltage. Moreover, EHD influences on the packed bed surface more than the inside. This is because EHD induces secondary flow, so-called corona wind. The effect of this corona wind circulating above packed bed enhances the mass transfer, and destabilizes the boundary layer on the surface. Consequently, convective heat transfer coefficient is enhanced, and then heat from hot-air flow can much transfers into packed bed.

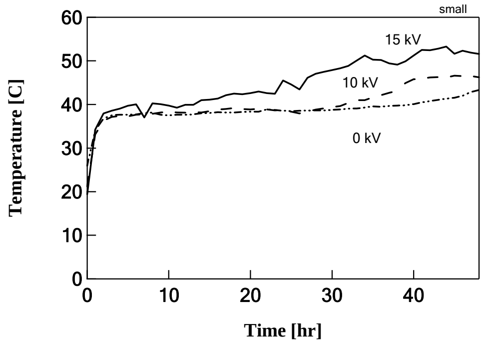

Fig. 5 Surface temperature (z = 0 cm) of 0.125-mm-bead packed bed in various voltages.

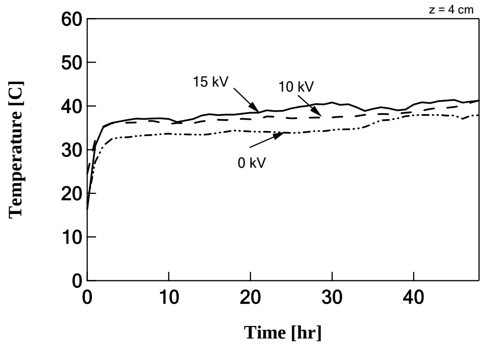

Fig. 6 Temperature of 0.125-mm-bead packed bed at z = 4 cm.

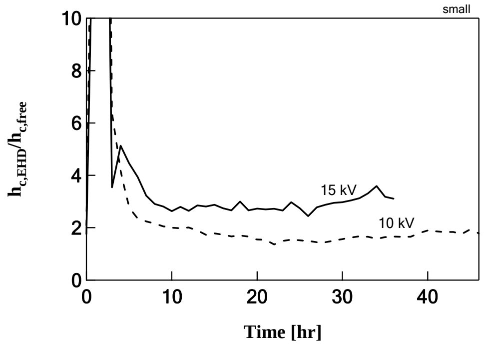

Fig. 7 Enhancement of heat transfer coefficient in case of packed bed with 0.125-mm bead.

In this study, the enhancement of heat transfer due to EHD is defined as the ratio of convective heat transfer coefficient with EHD to convective heat transfer coefficient with free air, i.e. ($h_{c.EHD} / h_{c,free}$), and the results are shown in Fig. 7. In warm-up period, this ratio increases rapidly. In constant drying period (constant surface temperature), the ratios approximately are 2 and 3 when V = 10 and 15 kV, respectively.

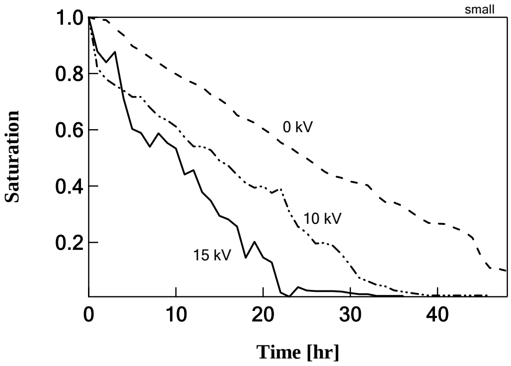

Fig. 8 Comparison on water saturation of 0.125-mm-bead packed bed in various voltages.

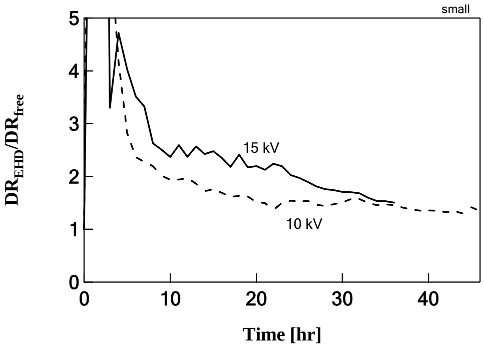

Fig. 9 Enhancement of rate of mass transfer in 0.125-mm-bead packed bed.

As shown in Fig. 8, with EHD, water saturation in packed bed rapidly decreases. In constant rate of drying period, the drying rate with EHD is approximately 2 – 2.5 times higher than that with hot-air flow only, as shown in Fig. 9.

Heat transfer in 0.38-mm-bead packed bed is shown in Fig. 10. This is shown that EHD enhances heat transfer in packed bed. When voltage is applied, temperature difference is clearly observed.

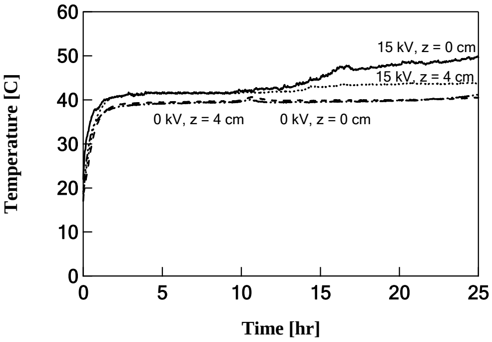

Fig. 10 Temperature of 0.38-mm-bead packed bead in various voltages at z = 0 and 4 cm.

4.2 Effects of porosity in packed bed

Influence of porosity or glass bead size on heat and mass transfer are shown in Fig. 11 - 12. After the constant rate of drying period, surface temperature of fine packed bed rapidly increases, while the case in coarse packed bed gradually increases.

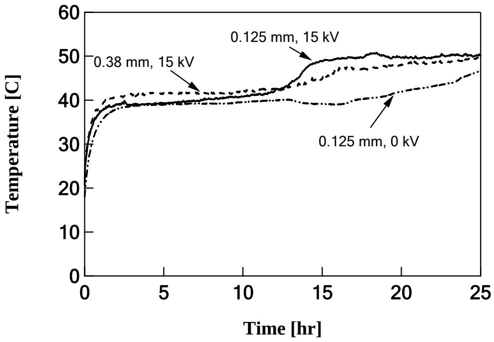

Fig. 11 Comparison on surface temperature (z = 0 cm) of 0.38-mm- and 0.125-mm-bead packed beds

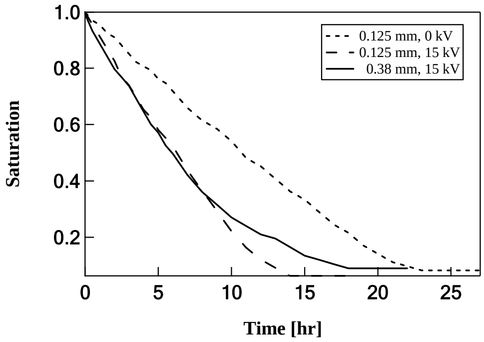

Fig. 12 Comparison on saturation in packed bead with different glass bead sizes.

4.3 Double-layer packed bead

In case of double-layer packed, one more fiber optic wire is placed at z = 3 cm, i.e. interface layer.

Figure 13 and 14 show temperature in packed bead of F-C case. As shown in Fig. 13, in the warm-up period, all temperatures in this packed bed rise up steadily. Later, they remain constant, and surface temperature of 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. As explained above, fine packed bed has the capillary pressure (p_c) higher than coarse packed bed. In the initial state, if both layers have same saturation, then difference of capillary pressure will be occurred. Effect of capillary action in the fine bead layer (upper layer) will induce the moisture from the coarse bead layer (lower layer) up to its layer. This results void in the lower layer to be filled with more the vapor phase. Therefore, with a same heat flux, temperature in lower layer becomes higher. As moisture evaporating process proceeds, the temperatures are constant; heat mainly is used for changing phase. When 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.

Figure 15 and 16 show temperatures when coarse beads overlay fine beads (C-F). 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 electrical voltages are applied, 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.

It is shown in Fig. 17 that C-F cases have the moisture removal much lower than F-C cases. With influence of EHD, the drying rate can be increased. In addition, rate of drying of F-C cases is about 3.13 – 3.7 times higher than that of C-F case. Moreover, with voltage applied, the drying rate is improved about 1.5 – 1.97 times.

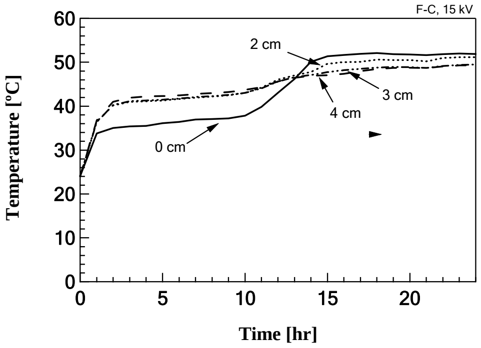

Fig. 13 Temperature in F-C case when V = 15 kV.

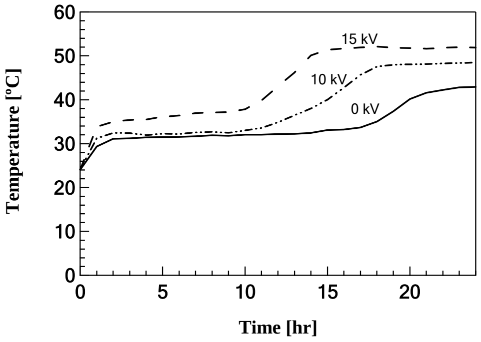

Fig. 14 Temperature at z = 0 cm in F-C case in various voltages.

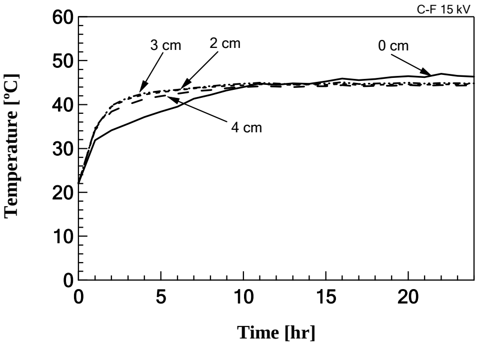

Fig. 15 Temperature in C-F case when V = 15 kV.

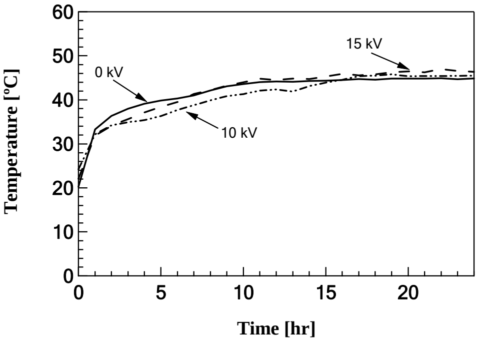

Fig. 16 Temperature at z = 0 cm in C-F case in various voltages.

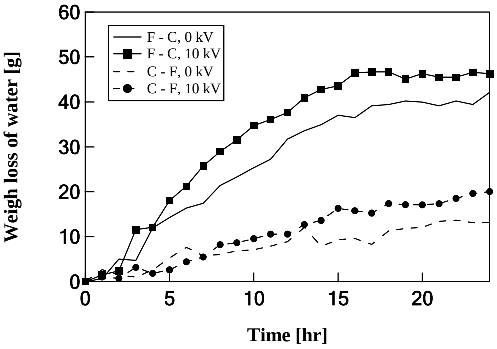

Fig. 17 Comparison on weight loss of water from packed bed in various cases.

5. Conclusions

Effect of electrical voltage, porosity, porous structure on heat and mass transfer in the porous packed beds are experimentally investigated. The conclusions of this study are:

1 Circulating wind enhances the convective heat transfer coefficient and evaporation rate on the packed bed surface exposed to hot-air flow, resulting enhancement of in rate of heat and mass transfer in packed bed. In addition, the enhancement relies on the magnitude of voltage, and porosity of packed bed.
2 In single-layer packed bed, high capillary pressure occurs in large porosity, resulting in high rate of water removal.
3 Due to effect of capillary pressure difference, heat and mass transfer in double-layer packed bed exhibit unlike in the single layer cases. With retarding of moisture motions in the upper layer in C-F cases, moisture in the lower layer slowly move towards the upper layers, resulting in low temperature. While F-C cases conduct moisture in the lower layers towards the upper layers better. With voltage applied, the drying rate is improved about 1.5 – 2 times. In addition, the drying rate of F-C cases is about 3 – 3.7 higher than that of C-F cases.

6. Acknowledgement

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7. References

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