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Analysis of heat and mass transfer enhancement in porous material subjected to electric fields (effects of particle sizes and layered arrangement)

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A B S T R A C T

This research experimentally investigates the influences of electrical voltage, particle sizes and layer arrangement on the heat and mass transfer in porous packed bed subjected to electrohydrodynamic drying. The packed bed consists of a single and double layers of glass beads, water and air. Sizes of glass beads are 0.125 and 0.38 mm in diameter. Electric fields are applied in the range of 0–15 kV. Average velocity and temperature of hot airflow are controlled at 0.33 m/s and 60 °C, respectively. The results show that the convective heat transfer coefficient and drying rate are enhanced considerably with a Corona wind. In the single-layered case, due to effects of porosity, the packed bed containing small beads has capillary pressure higher than that with big beads, resulting in higher removal rate of water and higher rate of heat transfer. Considering the effect of capillary pressure difference, temperature distribution and removal rate of moisture in the double-layered case appear to be different than those observed in the single-layered case. Moreover, in the double-layered case, the fine-coarse packed bed gives drying rate higher than that given by the coarse–fine packed bed.

1. Introduction

There has been a continuous effort to achieve a better technological performance in drying processes, which provide high quality products and minimize the energy cost. Hot-air drying technique is widely used in agricultural industries for removing the moisture content from products. However, its drying period is long, resulting in large energy consumption. In order to improve the drying rate, many researchers have paid much attention in a development of hot-air drying by cooperating the conventional method with the other methods, e.g., microwave [1–6], infrared [7–10], and electric fields (Electrohydrodynamics, EHD) [11–13]. In order to increase the removal rate of moisture within materials, microwave irradiation penetrates in the bulk of material, and creates a heat source at a certain location. However, microwave drying is known to result in a poor quality product if it is not properly applied [2,3]. To heat the surface region, infrared radiation is transmitted through water at a short wavelength, while it is absorbed on the surface at a long wavelength [8]. This way of drying process is suitable to dry thin layers of material with large surface exposed to radiation. In electrohydrodynamic drying, high-intensity electric field is applied to airflow in order to induce the secondary flow or circulating flow, so-called Corona wind. The net effect of this secondary flow is additional mixing of fluids and destabilization of boundary layer, therefore leading to a substantial increase in mass transfer coefficients [11].

Due to simultaneous heat and mass transfer taking place during drying process, mechanisms of drying in porous materials are complicated, and still have been investigated by many researchers. Schröder et al. [14] measured heat transfer between particles and nitrogen gas flow in packed bed. They reported that increasing gas flow led to higher heat transport coefficient. Alem-Rajabif and Lai [11] experimentally investigated the drying rate of partially wetted glass bead subjected to electric field. In their experiments, a wire electrode and a copper plate were located on the upper and lower of 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 drying with the positive Corona was generally greater than that with the negative Corona. This result was consistent with the experimental setup by Alem-Rajabif and Lai [11], Lai and Lai [12] who examined the influence of electric field parameters on the drying rate of a packed bed. Their results showed that drying rate depended on the strength of the electric field and the velocity of the cross flow. Without cross flow, the drying rate increased linearly with the applied voltage, while the influence of Corona wind was suppressed by high cross-flow velocity.

To explain the drying mechanisms, Ratanadecho et al. [4] experimentally and numerically studied the microwave drying in unsaturated material with different porosities. They found that packed bed with a small bead size had capillary forces and drying rate higher than that with a big bead size. From the above literatures,

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Nomenclature

C	coarse bead
d	diameter of glass bead (mm)
D_h	hydraulic diameter (m)
F	fine bead
h_c	convective heat transfer coefficient (W/m^2 K)
h_v	latent heat of vaporization (J/kg)
K	permeability (m^2)
M	mass (kg)
$\dot{m}$	mass flux of evaporation (kg/m^2 s)
p	pressure (Pa)
R_e	Reynolds number
S	saturation
S_{eff}	effective water saturation associated with the irreducible water saturation
T	temperature (°C)
∇T	temperature gradient in packed bed (°C)
V	volume (m^3)
X	moisture content
z	distance from surface of packed bed

Greek letters

δ	depth of packed bed (mm)
λ_{eff}	the effective thermal conductivity (W/m K)
μ	viscosity (Pa s)
ϕ	porosity (m^3/m^3)
ρ	density (kg/m^3)
σ	surface tension (Pa m)

Subscripts

a	air
c	capillary
eff	effective
EHD	air with electric fields
$free$	free air
g	gas
l	liquid
s	solid
sur	surface
w	water

only the researches by Ratanadecho et al. [4–6] had studied the mechanisms of heat and mass transfer in the packed bed. However, behaviour of microwave heating is different from hot-air heating. To get further understanding in the mechanisms of drying with surface heating, this study experimentally investigates and analyzes the heat and mass transfer within single- and double-layered porous packed bed subjected to hot-air flow and electric fields. Moreover, effects of particle sizes and layered arrangement are also examined.

2. Theory

2.1. Drying enhancement with Corona wind

For drying with hot-air flow, the idea of heat-and-mass transfer enhancement by utilizing EHD is shown in Fig. 1. When hot-air flow exposes to high-voltage electric fields, the flow is circulated. Then this secondary flow enhances the convective heat transfer and depresses the influence of boundary layer on the packed-bed surface. This causes much of moisture on surface to vaporize towards the hot-air flow, and allows larger amount of heat to transfer into the packed bed. Consequently, the drying rate is substantially enhanced.

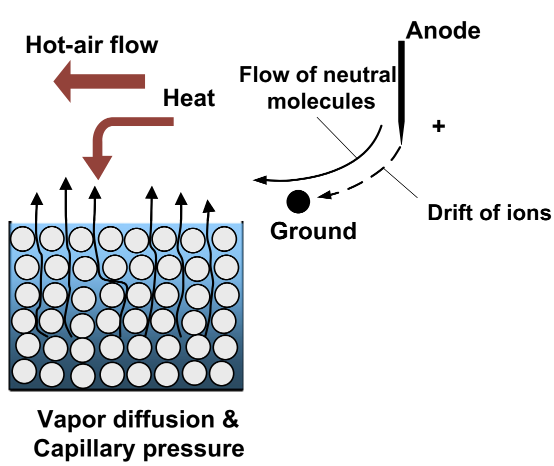

Fig. 1. Idea of enhancement of heat and mass transfer with corona wind.

2.2. Related equations

Water saturation (S) of a porous medium with respect to a particular fluid is defined as

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

Moisture content (X) in porous material is the ratio of total mass of water (M_w) to total mass of dry solid (M_s), i.e.

$$X = \frac{M_w}{M_s} \quad (2)$$

Eq. (2) can be written in term of water saturation as,

$$X = \frac{\phi \rho_w}{(1-\phi)\rho_s} S \quad (3)$$

where ϕ is porosity of material (m^3/m^3), ρ_{w} and ρ_{s} are density of water and solid (kg/m^3), respectively.

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

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

where λ_{eff} is effective thermal conductivity (W/m K), and ∇T is temperature gradient in packed bed (°C/m).

Based on the experimental results of Aoki et al. [15], the effective thermal conductivity is further assumed to be a function of water saturation and is defined as

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

Exchange of energy at surface of packed bed exposed to airflow can be calculated by

$$\lambda_{eff} \frac{\partial T}{\partial z} = -h_c(T_a - T_{sur}) + \dot{m}_w h_v \quad (6)$$

where h_c is convective heat transfer coefficient (W/m^2 K), $\dot{m}_w$ is mass flux of evaporation (kg/m^2 s) or rate of weight loss of water from porous media, h_v is latent heat of vaporization (J/kg), T_{sur} is temperature on material surface (°C), and T_a is air-flow temperature (°C).