

The Analysis of Drying Kinetics During Convective Drying of Granular Packed Bed

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Abstract

In this paper, the comparison between experimental and theoretical results for a convective drying of layered porous packed bed, i.e, layered granular packed beds, is presented. To elucidate on the physics of the process at a fundamental level, a complete model is proposed, which considers the intricate link that transpires between the temperature, total pressure, moisture transport and moving boundary phenomena throughout the sample during convective drying. Most importantly, it focuses on the analysis of the effects of particle size and the structure of layered granular packed bed on the overall drying kinetics. The results showed that the particle size and structure of layered granular packed bed are influenced on the convective drying kinetics considering the interference between capillary flow and vapor diffusion in the layered granular packed bed. The predicted results are in good agreement with the experimental results.

1. Introduction

From a theoretical standpoint, the drying process of porous media is a complicated process involving simultaneous, coupled heat and mass transfer phenomena. Modeling simultaneous heat and mass transport in porous media is of growing interest in wide range of new technology, in order to improve process performance and energy utilization, new technology such as tertiary oil recovery process, medical application, geothermal analysis, freeze drying process, forest product, building industry, food stuffs and microwave drying process have been applied. Knowledge of heat and mass transfer that occurs during convective drying of porous materials is crucial to reduce energy cost of drying, equipment and process design, and preserve the quality of varying product.

The mathematical models for simultaneous heat and mass transfer in uniform-porous media sample have been studied by many authors (Ben Nasrallah and Perre [1]; Kaviany and Mittal [2]; Turner [4]; and our group (Ratanadecho et al. [5]-[8])). However, some kind of porous material considered that the distributions of

grain sizes within porous body are not uniform throughout, and it can be considered as a multi-layered porous samples. Typical applications of these materials include the tertiary oil recovery process, geothermal analysis, asphaltic concrete pavements process and food stuffs. Therefore, knowledge of heat and mass transfer that occurs during convective drying of multi-layered porous materials is necessary to provide a basis for fundamental understanding of transport phenomena in non-uniform body.

In some more recent research, Ratanadecho et al. (5) is carried out the first systematical study on drying process of multi-layered porous packed bed by microwave energy, however, no theoretical confirmation is reported.

Due to the limited amount of theoretical and experimental work on convective drying of multi-layered sample, the various effects are not fully understood and a number of critical issues remain unresolved. These effects of particle size and the structure of layered porous packed bed on the overall drying kinetics have not been systematically studied. Therefore, the specific objectives of this work are to:

- (1) Extend the previous work of Ratanadecho et al. (5) to include the mathematical model for the convective drying of multi-layered porous packed bed,
- (2) solve the mathematical model numerically.
- (3) compare the numerical results with experimental measurements,

2. Experimental Apparatus

Figure 1(a) shows the experimental apparatus for the convective drying system. The hot air generated using electric-hot air generation, it is traveled through the air duct toward the upper surface of two samples which are located inside the test section. The out side walls of test section are covered with insulation to ensure that only a minimal amount of heat loss to the ambient. In addition, the outlet of airflow and temperature ranges can be

adjusted at control panel of electric-hot air generation.

As shown in Fig. 1(b), the samples are unsaturated porous packed bed, which compose of glass beads, water and air. The samples are prepared in two configurations: a single-layered porous packed bed ($d=0.15$ mm and $d=0.4$ mm and $\delta=40$ mm) and a two-layered porous packed bed, respectively. In the case of two-layered porous packed bed which is prepared in two configurations, namely, (a) the fine bed is above the coarse bed, F-C bed and (b) the fine bed is under the coarse bed, C-F bed.

Here

Fine bed $\rightarrow d=0.15$ mm, $\delta=20$ mm

Coarse bed $\rightarrow d=0.4$ mm, $\delta=20$ mm

The samples are inserted in the test section. The temperature distributions within the sample are measured using thermocouples which are placed in the center of the sample at each 5 mm interval. In each test run, the weight loss of the sample is measured by high precision mass scale.

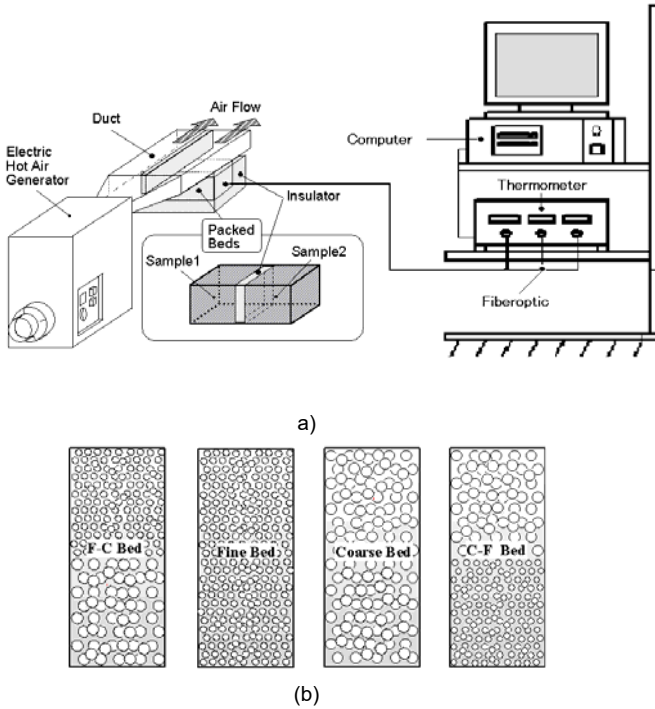


Fig. 1 Schematic of experimental facility: (a) Equipment setup; (b) Multi-Layered porous packed bed (Sample)

3. Mathematical Formulation of Problem

A schematic diagram of the convective drying model for multi-layered porous packed bed is shown in Fig. 2. When porous packed bed is heated by hot air flowing over the upper surface of packed bed, the heat is transfer from the top of packed bed into the interior. Therefore, the temperature gradient is formed in porous packed bed, and the liquid phase at the upper surface of packed bed evaporates by the variation of saturated vapor concentration corresponding to this temperature gradient. As drying progresses, the liquid phase supplying to surface by

capillary action becomes insufficient to replace the liquid being evaporated. The latter arises from the fact that the dry layer takes place over small effective surface or on a front retreating from the surface into the interior of the sample dividing it into two layers; dry layer and two-phase layer, which is separated by the moving evaporation front. Inside the two-phase layer where liquid water and gas phases coexist and the main mechanism of moisture transfer is capillary pressure. Inside the dry layer, only gas phase exists and transfers toward either the upper or lower surface by the balance of the total pressure gradient of gas phase and gravity.

Since the formulation of dry layer acts as thermal resistance against the heat transfer from the hot air, drying rate decreases remarkably in comparison with case that the formulation of dry layer is not started. Generally, this state is well known as period of falling rate. On the other hand, for the state of before formulation of dry layer, this state is called as period of constant rate because the drying rate is nearly constant.

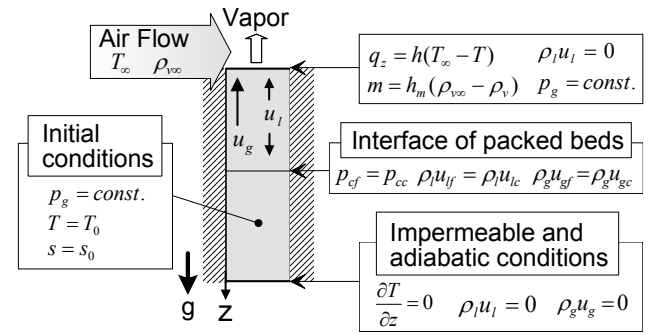


Fig.2 Physical model

In analysis, the main assumptions involved in the formulation of the transport model are (Ratanadecho et al. (7)):

1. The capillary porous material is rigid,
2. local thermodynamic equilibrium among each phase is assumed,
3. the gas phase is ideal in the thermodynamic sense,
4. the contribution of convection to energy transport is included,
5. Darcy's law holds for the liquid and gas phases,
6. in a macroscopic sense, the porous packed bed is assumed to be homogeneous and isotropic, and liquid water not bound to the solid matrix. Therefore, the volume average model for a homogeneous and isotropic material can be used in the theoretical model and analysis.

By conservation of mass and energy in the multi-layered porous packed bed, the governing equation of mass and energy for all phases in each layer can be derived using the volume-averaging technique. The main basic equations for two-phase layer and dry layer are given by following equations:

Basic equation for two-phase layer

The mass conservation equation

Moisture

$$\begin{aligned} & \frac{\partial}{\partial t} \{ \rho_l \phi_j s_j + \rho_v \phi_j (1-s_j) \} + \\ & \frac{\partial}{\partial z} \left[\rho_l \frac{K_j K_{rl,j}}{\mu_l} \left(\frac{\partial p_{c,j}}{\partial z} - \frac{\partial p_g}{\partial z} + \rho_l g \right) + \right. \\ & \left. \rho_v \frac{K_j K_{rg,j}}{\mu_g} \left(-\frac{\partial p_g}{\partial z} + \rho_g g \right) - \rho_g D_m \frac{\partial}{\partial z} \left[\frac{\rho_v}{\rho_g} \right] \right] = 0 \end{aligned} \quad (1)$$

Air phase

$$\begin{aligned} & \frac{\partial}{\partial t} \{ \rho_a \phi_j (1-s_j) \} + \\ & \frac{\partial}{\partial z} \left[\rho_a \frac{K_j K_{rg,j}}{\mu_g} \left(-\frac{\partial p_g}{\partial z} + \rho_g g \right) - \rho_g D_m \frac{\partial}{\partial z} \left[\frac{\rho_a}{\rho_g} \right] \right] = 0 \end{aligned} \quad (2)$$

Gas phase

$$\frac{\partial}{\partial t} \{ \rho_g \phi_j (1-s_j) \} + \frac{\partial}{\partial z} \left[\rho_g \frac{K_j K_{rg,j}}{\mu_g} \left(-\frac{\partial p_g}{\partial z} + \rho_g g \right) \right] = n \quad (3)$$

The energy conservation equation

$$\begin{aligned} & \frac{\partial}{\partial t} \{ (\rho_l c_{pl} \phi_j s_j + \rho_g c_{pg} \phi_j (1-s_j) + \rho_p c_{pp} (1-\phi_j)) T + h_{lv} \rho_v \phi_j (1-s_j) \} \\ & + \frac{\partial}{\partial z} \left\{ (\rho_l c_{pl} u_{l,j} + \rho_g c_{pg} u_{g,j}) T + h_{lv} \left[\rho_v u_{g,j} - \rho_g D_m \frac{\partial}{\partial z} \left(\frac{\rho_v}{\rho_g} \right) \right] \right\} \\ & = \frac{\partial}{\partial z} \left[\lambda_{eff} \frac{\partial T}{\partial z} \right] \end{aligned} \quad (4)$$

3.2 Basic equation for dry layer

Considering gas and heat transfer in the dry layer, since no liquid water exists within the void of porous packed bed, the basic equations for this layer are given by following equations; taking into account the transfer of gas phase which includes the diffusions of water vapor and air and heat transfer as follows:

$$\frac{\partial}{\partial t} \{ \rho_v \phi_j \} + \frac{\partial}{\partial z} \left[\rho_v \frac{K_j K_{rg,j}}{\mu_g} \left(-\frac{\partial p_g}{\partial z} + \rho_g g \right) - \rho_g D_m \frac{\partial}{\partial z} \left(\frac{\rho_v}{\rho_g} \right) \right] = 0 \quad (5)$$

$$\frac{\partial}{\partial t} \{ \rho_a \phi_j \} + \frac{\partial}{\partial z} \left[\rho_a \frac{K_j K_{rg,j}}{\mu_g} \left(-\frac{\partial p_g}{\partial z} + \rho_g g \right) - \rho_g D_m \frac{\partial}{\partial z} \left(\frac{\rho_a}{\rho_g} \right) \right] = 0 \quad (6)$$

$$\frac{\partial}{\partial t} [(\rho c_p)_{T,j} T] + \frac{\partial}{\partial z} [(\rho_a c_{pa} + \rho_v c_{pv}) w_{g,j} T] = \frac{\partial}{\partial z} \left[\lambda_{eff} \frac{\partial T}{\partial z} \right] \quad (7)$$

$$(\rho c_p)_{T,j} = \rho_g c_{pg} \phi_j + \rho_p c_{pp} (1-\phi_j) \quad (8)$$

where we use $n=0$ and $s=0$ in the dry layer.

Furthermore, the constitutive equations for relative permeabilities, K_r , capillary pressure, p_c and the effective thermal conductivity are already presented in previous work (Ratanadecho et al. [6]).

3.3 Boundary conditions

The boundary conditions are already shown in Fig. 2, except the boundary condition at the drying front where water saturation approached to irreducible value ($s=s_{ir}$), mass and energy conservation equations at this interface ($z=R$) are given as

follows:

$$\rho_l \phi s \frac{\partial R}{\partial z} = \rho_v u_v|_l + \rho_l u_l|_l - \rho_v u_v|_d \quad (9)$$

$$\rho_a u_a|_d = \rho_a u_a|_l \quad (10)$$

$$h_{lv} \rho_l \phi s \frac{\partial R}{\partial t} = -\lambda_{eff} \frac{\partial T}{\partial z}|_l + \lambda_{eff} \frac{\partial T}{\partial z}|_d + \rho_l u_l c_{pl} T|_l \quad (11)$$

Initially, the temperature, the total pressure and the moisture content are uniform within multi-layer porous packed bed.

3.4 The coordinate transformation

In this study, the governing equations of water and heat transport including the moving boundary front are solved by using coordinate transformation technique based on boundary fixing method coupled with an implicit time schemes (Murray and Landis, [9]). With details omitted, Corresponding to Eqs. (1)-(7), after some mathematical manipulations, the mass and energy transfer equation in each layer can be then transformed to following equation, respectively:

Dry layer

$$\frac{\partial}{\partial t} (\rho_v \phi_j) - \frac{\alpha}{R} \frac{\dot{R}}{\partial \alpha} (\rho_v \phi_j) + \frac{1}{R} \frac{\partial}{\partial \alpha} \left[\rho_v u_{g,j} - \rho_g D_m \frac{1}{R} \frac{\partial}{\partial \alpha} \left(\frac{\rho_v}{\rho_g} \right) \right] = 0 \quad (12)$$

$$\frac{\partial}{\partial t} (\rho_a \phi_j) - \frac{\alpha}{R} \frac{\dot{R}}{\partial \alpha} (\rho_a \phi_j) + \frac{1}{R} \frac{\partial}{\partial \alpha} \left[\rho_a u_{g,j} - \rho_g D_m \frac{1}{R} \frac{\partial}{\partial \alpha} \left(\frac{\rho_a}{\rho_g} \right) \right] = 0 \quad (13)$$

$$\begin{aligned} & \frac{\partial}{\partial t} \{ (\rho_g c_{pg} \phi_j + \rho_p c_{pp} (1-\phi_j)) T \} - \frac{\alpha \dot{R}}{R} \frac{\partial}{\partial \alpha} \{ (\rho_g c_{pg} \phi_j + \rho_p c_{pp} (1-\phi_j)) T \} \\ & + \frac{1}{R} \frac{\partial}{\partial \alpha} \{ (\rho_g c_{pg} u_{g,j}) T \} = \frac{1}{R^2} \frac{\partial}{\partial \alpha} \left[\lambda_{eff} \frac{\partial T}{\partial \alpha} \right] \end{aligned} \quad (14)$$

Two-phase layer

$$\begin{aligned} & \frac{\partial}{\partial t} \{ \rho_l \phi_j s_j + \rho_v \phi_j (1-s_j) \} - \frac{(1-\beta)}{L-R} \frac{\dot{R}}{\partial \beta} \{ \rho_l \phi_j s_j + \rho_v \phi_j (1-s_j) \} \\ & + \frac{1}{L-R} \frac{\partial}{\partial \beta} \left[\rho_l u_{l,j} + \rho_v u_{g,j} - \rho_g D_m \frac{1}{L-R} \frac{\partial}{\partial \beta} \left(\frac{\rho_v}{\rho_g} \right) \right] = 0 \end{aligned} \quad (15)$$

$$\frac{\partial}{\partial t} (\rho_a \phi_j) - \frac{(1-\beta)}{L-R} \frac{\dot{R}}{\partial \beta} (\rho_a \phi_j) + \frac{1}{L-R} \frac{\partial}{\partial \beta} \left[\rho_a u_{g,j} - \rho_g D_m \frac{1}{R} \frac{\partial}{\partial \beta} \left(\frac{\rho_a}{\rho_g} \right) \right] = 0 \quad (16)$$

$$\frac{\partial}{\partial t} (\rho_g \phi_j) - \frac{(1-\beta)}{L-R} \frac{\dot{R}}{\partial \beta} (\rho_g \phi_j) + \frac{1}{L-R} \frac{\partial}{\partial \beta} [\rho_g u_{g,j}] = n \quad (17)$$

$$\begin{aligned} & \frac{\partial}{\partial t} \{ (\rho_l c_{pl} \phi_j s_j + \rho_g c_{pg} \phi_j (1-s_j) + \rho_p c_{pp} (1-\phi_j)) T + h_{lv} \rho_v \phi_j (1-s_j) \} \\ & - \frac{(1-\beta) \dot{R}}{L-R} \frac{\partial}{\partial \beta} \{ (\rho_l c_{pl} \phi_j s_j + \rho_g c_{pg} \phi_j (1-s_j) + \rho_p c_{pp} (1-\phi_j)) T + h_{lv} \rho_v \phi_j (1-s_j) \} \\ & + \frac{1}{L-R} \frac{\partial}{\partial \beta} \left\{ (\rho_l c_{pl} u_{l,j} + \rho_g c_{pg} u_{g,j}) T + h_{lv} \left[\rho_v u_{g,j} - \rho_g D_m \frac{1}{L-R} \frac{\partial}{\partial \beta} \left(\frac{\rho_v}{\rho_g} \right) \right] \right\} \\ & = \frac{1}{(L-R)^2} \frac{\partial}{\partial \beta} \left[\lambda_{eff} \frac{\partial T}{\partial \beta} \right] \end{aligned} \quad (18)$$

4. Numerical Calculation

The coupled non-linear set of equations (Eqs. (1)-(3) and Eq. (4)) in regard to water saturation or moisture content, s , pressure of gas phase, p_g and temperature, T , are solved numerically by

using the finite control volume method (Patankar, [10]). The basic strategy of finite control volume discretization method is to divide the calculated domain into a number of control volumes and then integrate the conservation equations over this control volume over an interval of time $[t, t + \Delta t]$.

At each time increment, the nodal value of moisture content, pressure of gas phase and temperature are solved iteratively and convergence is checked on both variables. The Newton-Raphson method is employed at each iteration to quicker the convergence.

After the beginning of formulated dry layer, the set of equations are numerically solved by using Landua transformation technique (Eqs. (12)-(18)) with certain jump condition at the moving evaporation front.

5. Result and Discussion

The experimental results for convective drying of multi-layered porous packed beds are compared with mathematical model simulations. One aspect of model verification is to compare drying data from experiments run under different conditions with mathematical simulations using parameter values as follows;

$s_0 = 0.5$, $s_{ir} = 0.06$, $T_0 = 30$ [C°], $T_\infty = 80$ [C°], $U_\infty = 1.2$ [m/s], $h_c = 15$ [W/m² K]. The other physical properties were already presented in [5].

5.1 Moisture profiles within multi-layered porous packed bed

Figures 3(a) and (b) show the predicted moisture content profiles at various times and locations within the single-layered (F bed and C bed) and two-layered porous packed beds (F-C bed and C-F bed). In the case of single-layered porous packed bed, the moisture content continuously decreases toward the surface. Since the surface saturation decreases setting up a saturation gradient which draws liquid water toward the surface through capillary action while the water vapor which moves towards the surface due to a gradient in the vapor partial pressure. However, the internal moisture content transfer is mainly attributable to capillary flow of liquid water through the voids for this stage of drying. The following discussion refers to the effect of particle size on moisture migration mechanism under the same conditions for the single-layered porous packed bed. In Fig. 3(a), the observed moisture content profiles at the leading edge of the sample in the case of fine bed (F bed) are higher than that in the case of coarse bed (C bed). This is because of the fine bed or small particle size (which corresponds to a higher capillary pressure) can cause moisture to reach the surface at a higher rate than that case of coarse bed, i.e., large particle size. On the other hand, in the case of coarse bed, the moisture profiles at the leading edge of the sample are always lower as compared with the small particle size due to the lower capillary pressure inside the sample and the gravitational effect. Continued drying processes eventually cause the average of moisture level inside the porous packed bed would

decrease, especially at the leading edge of upper layer (Fig. 3(b)). When the moisture content at the upper surface (surface saturation) approaches to the irreducible (s_{ir}) where the liquid water becomes discontinuous (pendular state), the liquid water supply to surface by capillary action become insufficient to replace the liquid being evaporated. The latter arises from the fact that the dry layer takes place over small effective surface or on a front retreating from the surface into the interior of the sample dividing it into two layers, dry layer and two-phase layer. The discontinuity of the temperature gradient close to the drying front, is a result of heat flux necessary for evaporation and effective thermal conductivity falls considerably resulting in a resistance of the heat flow rate. A further consequence of premature drying of the outer dry layer, is that the local temperature of sample will reach that of drying medium (hot air).

Next, in the case of two-layered porous packed beds (F-C bed and C-F bed), the moisture content profiles become discontinuous at the interface between two layers, namely, though the moisture content in the upper layer becomes higher than that lower layer in the case of F-C bed, while the moisture content in the upper layer becomes lower than that case of C-F bed. This is because the equilibrium water saturation under the same capillary pressure differs according to the particle sizes where the small particle size corresponds to higher water saturation. Therefore, the drying kinetics are strongly influenced by the difference in this water saturation. Continued drying process (Figure 3(b)) cause the average of moisture level inside the F-C bed would decrease quickly in comparison with other cases. In the case of C-F bed, in contrast to that F-C bed, the moisture content inside upper layer (C bed) displays very lower and the formation of dry layer establishes rapidly while the moisture content inside the lower layer (F bed) remains higher. This is mainly due to the C bed (which corresponds to a lower capillary pressure) located above the F bed retards the upward migration of liquid water through the interface between two layers and also due to the effect of gravitational force.

Figure 4 shows the variations of mass of drying with respect to time for the difference in the structure of layered porous packed beds (F, C, F-C and C-F beds) under the condition as shown in Figure 3. It is observed that the variations of mass of drying and temperature are interrelated. The drying speed greatly different although the initial water saturation is the same, that is F-C bed becomes the fastest, and C-F bed becomes the slowest. This is understood easily by the difference in the moisture content in the neighborhood of upper surface of the porous packed beds shown by Figure 3. Namely, since the driving force of heat and mass transfer grows very large when moisture content and temperature neighborhood of upper surface are high. Consequently, the drying rate can be though to become fast.

In the microscopic sense, the drying rate rises up quickly in the early stages of drying process (which corresponds to a higher moisture content at the upper surface) and then decreases and reaches a plateau before decreasing again when the formation of drying is established. It is evident from the figure that the increase of drying rate can become significant when the F-C bed is utilized. This is a result of the strong effect of capillary pressure in F-C bed which easily overcomes the resistance caused by the lower permeability and maintains a good migrate of liquid water near the surface. However, in the case of C-F bed that the formation of dry layer is established rapidly at the early stage of drying whereas the moisture content within the lower layer is remaining higher. Therefore, the efficiency of drying process is the lowest in this case. The simulated results are in agreement with the experimental results for convective drying.

5.2 Temperature profiles within multi-layered porous packed bed

Figure 5 gives the measured and predicted temperature profiles with respect to time within the single-layered and two-layered porous packed bed, which correspond to that of $s_0=0.5$, $T_\infty=80$ (C°), $U_\infty=1.2$ m/s and bed depth (z) of 5 mm for F and F-C beds.

It is observed that at the early stage of drying process the temperature profiles in both cases are nearly the same. As drying progresses, the temperature profiles in both cases greatly increase. This is because the latent heat transfer due to the evaporation is retrained due to the decline of the mass transfer rate together with the decreasing of average moisture content. Nevertheless, the temperature profile in the case of F-C bed continuously rises faster than that case of F bed. This is because the F-C bed corresponds to a faster formation of dry layer, another abrupt temperature rise occurs as the dry bulb temperature is approached. On the other hand, in the case of F bed that the temperature increases slowly in comparison with F-C bed due to the late formation of dry layer. The prediction of the formation of dry layer estimated from the drop in the surface mass of drying and the rising in the drying temperature are marked in Figs. 4 and 5, respectively. In addition, at the longer drying times that the temperature at any instant tends to be constant shape throughout where the vapor diffusion effect plays an important role in the moisture migration mechanism because of the sustained vaporization that is generated within the sample. The simulated results are in agreement with the experimental results for convective drying.

6. Conclusions

In this studies, the effects of particle sizes and structure of layered porous packed bed on the overall drying kinetics are clarified in detail, considering the interference between capillary action, the diffusion of water vapor and latent heat transfer due to evaporation

in the multi-layered porous packed beds. The drying rate in the case of F bed is slightly higher than that case of C bed. This is because the F bed, i.e., small particle size, corresponds to a higher capillary pressure resulting in a faster drying time than that case a large particle size (C bed). Furthermore, for F-C bed, the drying curve displays a pronounced shape which differentiates it from the others, showing a faster drying time due to the strong effect of capillary action. It is found that the drying rate strongly depends on the moisture content at the permeable surface (surface saturation) on the convective heating side.

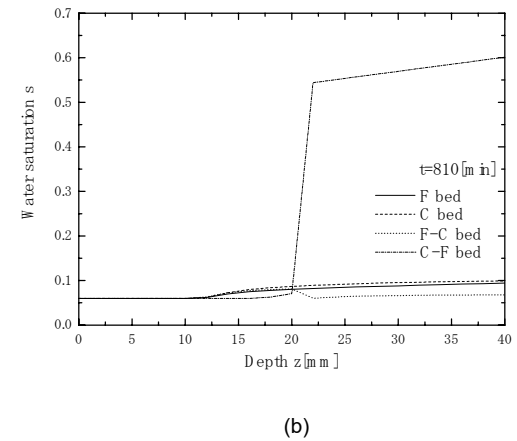
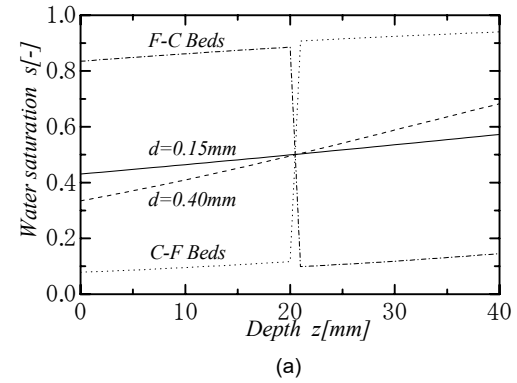


Fig. 3 The predicted result of water saturation in multi-layered porous packed bed as a function of locations (a) early stage of drying (b) long stage of drying

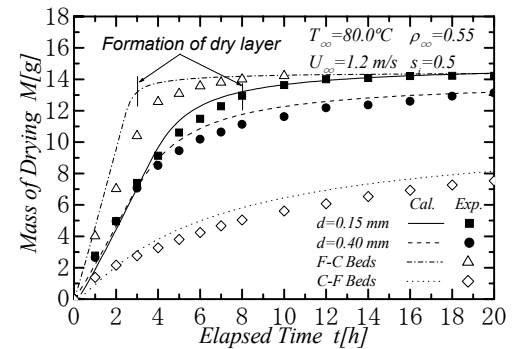


Fig.4 Time variation of the mass of drying

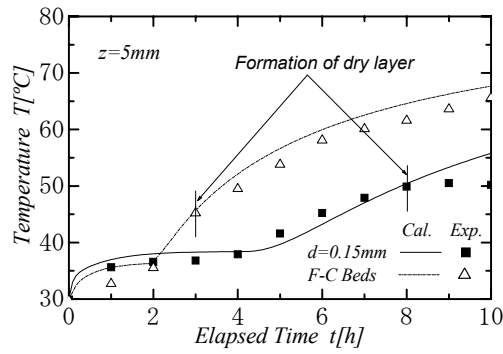


Fig.5 Time variation of the temperature at the position of $z=5\text{mm}$ in packed beds

Nomenclature

c_p	specific heat capacity [J/kgK]
d	diameter [m]
D_m	effective molecular mass diffusion
g	gravitational constant [m/s^2]
h_{lv}	latent heat of vaporization [J/kg]
h_c	heat transfer coefficient [$\text{W/m}^2\text{K}$]
h_m	mass transfer coefficient [$\text{W/m}^2\text{K}$]
K	permeability [m^2]
L	total length [m]
$\dot{n}$	volumetric evaporation rate [$\text{kg/m}^3\text{s}$]
p	pressure [Pa]
q	heat flux [W/m^2]
R	position of evaporation front [m]
s	water saturation
T	temperature [°C]
t	time [s]
U_∞	hot air velocity [m/s]
u	velocity [m/s]
z	coordinate axis [m]

Greek letters

δ	bed depth [m]
λ_{eff}	effective thermal conductivity [W/mK]
ϕ	porosity [m^3/m^3]
ρ	density [kg/m^3]
μ	viscosity [Pa s]
α, β	coordinate transformation

Subscripts

0	initial
a	air
c	capillary, coarse beads
e	effective
f	fine beads

g	gas
j	layer number
l	liquid water
p	particle
v	water vapor
∞	ambient

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