FACTORS INFLUENCING CONSTANT DRYING RATE OF WET GRANULAR BED IRRADIATED BY INFRARED RADIATION

ATSUSHI HASHIMOTO, KOTARO HIROTA, TAJIRO HONDA
AND MASARU SHIMIZU

*Division of Chemical & Biological Science and Technology,
Tokyo University of Agriculture & Technology, Tokyo 184*

ATSUO WATANABE

*National Food Research Institute, Ministry of Agriculture,
Forestry and Fisheries, Tsukuba 305*

Key Words: Drying, Infrared Radiation, Radiative Heat Transfer, Constant Drying Rate, Granular Bed

The present study aims at gaining a good understanding of the mechanism of infrared radiation drying of a wet granular bed in the constant-rate period. Our attention was focussed on the factors influencing the constant drying rate of a granular bed irradiated by infrared radiation. As the variables, the conditions of the granular bed (emissivity of the powder materials and the particle size of the powders) and the radiative heat source (the spectral distribution of irradiation power) were examined. Infrared radiation drying of the granular bed was performed and the heat transfer model in the constant-rate period was studied. The constant drying rate was calculated by using the model. The calculated results were quantitatively compared with the experimental results, and agreed consistently with the latter by taking account of the spectral distribution of absorption of irradiation power by the granular bed.

Introduction

Technologies for producing fine ceramics have improved. Infrared heaters made of fine ceramics with high emissivity in the region of far-infrared radiation (FIR) and low emissivity in the region of near-infrared radiation (NIR), are now being manufactured. We

classify infrared radiation in the region of wavelength longer than $3\mu\text{m}$ as FIR¹⁴⁾. Fundamental subjects regarding the applications of FIR are being actively investigated in many fields and many industries. The applications of FIR are of considerable interest for the following reasons: no need to heat the medium, simplification of apparatus, easy operation (thermal control), and clean working environment. For further progress in application technologies, a fundamental

* Received April 10, 1991. Correspondence concerning this article should be addressed to A. Hashimoto.

study of infrared radiation drying is desirable.

Infrared radiation drying is not a new technology. Yagi *et al.*^{17,18)} performed infrared radiation drying of granular materials. However, in their study the effect of emissivity of the powder materials on the drying rate was not discussed, and the effect of the particle size of the powders on the drying rate was not analyzed. Hirota *et al.*⁸⁾ discussed the constant drying rate of three kinds of wet granular beds irradiated by FIR. However, in their study the effects of spectral distributions of infrared absorption by the drying materials and of irradiation power on the drying character were not considered. Nishimura *et al.*^{15,16)} discussed an infrared radiation drying process of paint layer (the thickness was 0.1~0.4 mm), in which the irradiation power used for drying was mainly in the region of NIR. Therefore, it is difficult to apply the results to infrared radiation drying of many kinds of industrial materials and foods because of the thinness of the drying material.

The present study aims at gaining a good understanding of the mechanisms of infrared radiation drying of wet granular bed in the constant-rate period. Our attention was focussed on the factors influencing the constant drying rate. As the variables, the effects of the bed conditions and of the radiative heat source were examined. To study the effects of the bed conditions, the emissivity of powder materials and their particle sizes were considered. To study the effect of the radiative heat source, the spectral distribution of irradiation power was examined. We selected three kinds and several sizes of powders (alumina, silver and stainless steel powders) and used two types of infrared heaters (a FIR heater and a NIR heater). Infrared radiation drying was performed, and a heat transfer model for infrared radiation drying for a wet granular bed in the constant-rate period was studied.

1. Experimental Apparatus and Methods

1.1 Preparation of drying materials

A wet granular bed for the experiment of infrared radiation drying was prepared from powder and water. Alumina, silver and stainless steel powders were used as the samples. **Figure 1** shows the monochromatic emissivity of the powder materials^{3,12)}. **Table 1** shows the experimental conditions of the granular bed.

Figure 2 shows a scheme of the drying material. A wet granular bed is prepared in a shell made of stainless steel (14.5 × 48.5 mmφ). The side wall and the bottom of the shell were thermally insulated, and the insulator was covered with an aluminum foil to reflect infrared radiation. As shown in **Fig. 2**, CA-thermocouples sheathed by a stainless steel tube (0.25 mmφ) were placed horizontally at positions 1, 5 and 9 mm from the surface of the granular bed.

Fig. 1. Monochromatic emissivity of powder materials (flat surface)

Table 1. Experimental conditions of granular bed

Conditions	Powders		
	Alumina	Silver	Stainless
d_s [mm]	48.5		
l [mm]	10.0		
d_p [μm]	38 ~ 49	~ 49	63 ~ 125
	88 ~ 149	74 ~ 149	
	149 ~ 250		
e [—]	0.71 ~ 0.73	0.64 ~ 0.65	0.61

Fig. 2. Drying samples contained in sample holder

Fig. 3. Experimental apparatus for infrared radiation drying

1.2 Experimental apparatus

Figure 3 shows the apparatus for infrared radiation drying. The irradiation chamber is made of aluminum plates, with an infrared heater with reflector placed at the top. A FIR heater made of a mullite cylinder or a NIR heater made of a quartz cylinder was used as

the radiative heat source.

1.3 Drying methods

The electric power supplied to the heater was controlled by using a slidac. Figure 4 shows the monochromatic emission power at $W_s=400$ W. The irradiation distance from the heater to the top of the granular bed was 150 mm.

After a specified electric power was supplied to the heater and after the surface temperature of the heater, the room temperature and the room humidity reached steady-state condition, a wetted material was placed under the heater and infrared irradiation was carried out. During drying, the time behavior of the weight of the granular bed and the temperature distribution in the granular bed were measured by an electric balance and the thermocouples, respectively.

1.4 Measurement of irradiation power

Irradiation power, q_{ir} , was estimated experimentally from the *evaporation* rate of the water layer irradiated by infrared radiation. The methods were the same as those used in the previous study⁸⁾.

2. Model Calculation

2.1 Model of wet granular bed

Figure 5 shows a geometrical model of a wet granular bed. It is assumed that, near the surface, the wet granular bed is structured by the layers as shown in Fig. 5(a). Figure 5(b) is a geometrical model that simplifies Fig. 5(a). It is assumed that the surface of a particle in the first layer is covered with an optically very thin water film and that the void is filled with water. In Fig. 5(b), d is the depth of the water layer in the void and is given by the following equation.

$$d = \beta d_p \quad (1)$$

d_p is the particle size, and β is a parameter to be determined experimentally.

Figure 6 shows a heat transfer model for a wet granular bed irradiated by infrared radiation, in which the granular bed is placed horizontally and is heated from the upper side only by a radiative heat source. Drying is assumed to take place only on the surface of the granular bed in the constant-rate period, and heat transfer within the granular bed is assumed to be one-dimensional.

2.2 Absorption of infrared radiation by the granular-bed model

Consider the case in which the surface of the granular-bed model is irradiated by monochromatic irradiation power, $q_{ir,\lambda}$. And, for absorption of monochromatic infrared radiation by the granular bed, multiple reflection between the interfaces of water-air and of water-particle in the first layer or the second layer is considered (Fig. 7(a)). It is assumed that the spectral distribution of $q_{ir,\lambda}$ equals that of emission power from the infrared heater. And, it is

Fig. 4. Monochromatic emission power irradiated from unit surface area of infrared heater

Fig. 5. Model of wet granular bed. (a) Structured model; (b) Geometrical model

Fig. 6. Heat transfer model for wet granular bed irradiated by infrared radiation

assumed that the irradiation power is transmitted through the thin water film on the surface of the particle in the first layer and is absorbed by water in the void in the first layer.

Then the monochromatic radiation power absorbed by the granular bed, $q_{abs,\lambda}$, is expressed as the following equation:

$$q_{abs,\lambda} = (1 - e)q_{abs,p1\lambda} + e(q_{abs,w\lambda} + q_{abs,p2\lambda}) \quad (2)$$

Fig. 7. Radiative heat transfer model for wet granular bed irradiated by infrared radiation (a) Absorption; (b) Emission

where e is the void fraction of the granular bed, $(1-e)q_{abs,p1\lambda}$ and $eq_{abs,p2\lambda}$ are the monochromatic radiation power absorbed by the particle part in the first layer and in the second layer in the granular bed, respectively, and $eq_{abs,w\lambda}$ is the monochromatic radiation power absorbed by the water part in the void in the first layer.

$q_{abs,p1\lambda}$, $q_{abs,p2\lambda}$ and $q_{abs,w\lambda}$ are expressed by the following equations.

$$q_{abs,p1\lambda} = \frac{(1-r_{a\lambda})\epsilon_{p,\lambda}}{1-r_{l,\lambda}(1-\epsilon_{p\lambda})} q_{ir,\lambda} \quad (3)$$

$$q_{abs,p2\lambda} = \frac{(1-r_{a\lambda})\epsilon_{p,\lambda}\tau_{w\lambda}}{1-r_{l,\lambda}(1-\epsilon_{p\lambda})\tau_{w\lambda}^2} q_{ir,\lambda} \quad (4)$$

$$q_{abs,w\lambda} = \frac{(1-r_{a\lambda})(1-\tau_{w\lambda})\{1+(1-\epsilon_{p\lambda})\tau_{w\lambda}\}}{1-r_{l,\lambda}(1-\epsilon_{p\lambda})\tau_{w\lambda}^2} q_{ir,\lambda} \quad (5)$$

τ_w is the transmissivity of water in the void in the first layer, and r_a and r_l are external reflectivity and internal reflectivity of the water-air interface, respectively. ϵ_p is the emissivity of a flat plate made of powder material. q_{ir} is irradiation heat flux.

The total radiation power absorbed by the granular bed, q_{in} , is given by the following equation.

$$q_{in} = \int_0^\infty q_{abs,\lambda} d\lambda \quad (6)$$

2.3 Heat loss from the granular-bed model

Consider the heat loss from the granular bed in the constant-rate period. As the temperature through the granular bed is assumed to be constant in the constant-rate period, heat loss from the granular bed, q_{out} , is given by the following equation.

$$q_{out} = q_{evap} + q_{conv} + q_{rad} \quad (7)$$

q_{evap} , q_{conv} and q_{rad} in Eq. (7) are then latent heat flux due to evaporation, the convective heat flux on the granular bed and the net radiative heat flux, respectively, and can be expressed as the following equations:

$$q_{evap} = k_m \rho_s \left(\frac{Y_s^*}{1+Y_s^*} - \frac{Y_a}{1+Y_a} \right) \gamma \quad (8)$$

$$q_{conv} = h_c (T_s - T_a) \quad (9)$$

$$q_{rad} = q_{rad,p} + q_{rad,w} \quad (10)$$

Y_s^* is the saturated absolute humidity at the surface temperature of the granular bed, T_s , and γ is the latent heat of evaporation at T_s , h_c and k_m are respectively the heat and the mass transfer coefficients for natural convection^{1,2,4,5,13}. The first term, $q_{rad,p}$, and the second term, $q_{rad,w}$, of the right side of Eq. (10) express respectively the radiation power from the particle part in the first layer and that from the water part in the void in the first layer of the granular bed. As shown in Fig. 7(b), multiple reflection between the interfaces of water-air and of water-particle in the first layer is considered. Also, it is assumed that the radiation power from the particle part in the first layer is transmitted through the thin water film on the surface of the particle. But it is assumed that all of the radiation power from the particle part in the second layer is absorbed by water in the void in the first layer, because the depth of the water layer is thicker than about $50 \mu\text{m}$ and the bed temperature is much lower than the surface temperature of the infrared heater. Their terms are given by the following equations:

$$q_{rad,p} = \Phi_2 \epsilon_p (1-e) \sigma (T_s^4 - T_a^4) \quad (11)$$

$$q_{rad,w} = \epsilon_w e \sigma (T_s^4 - T_a^4) \quad (12)$$

$\Phi_2 \epsilon_p$ is the effective emissivity⁸⁾ of the particle part in the first layer, and Φ_2 can be expressed by Eq. (13).

$$\Phi_2 = \frac{1-r_l}{1-r_l(1-\epsilon_p)} \quad (13)$$

2.4 Estimation for constant drying rate

In the constant-rate period the heat balance Eq. (14) is satisfied.

$$q_{in} = q_{out} \quad (14)$$

From this relation, T_s and Y_s^* are obtained, and the constant drying rate, R_c , is given by the following equation:

$$R_c = k_m \rho_s \left(\frac{Y_s^*}{1+Y_s^*} - \frac{Y_a}{1+Y_a} \right) \quad (15)$$

3. Experimental Results

3.1 Effect of emissivity of powder materials

We selected three kinds of powders, whose

Fig. 8. Effect of emissivity of powder materials on R_c of wet granular bed irradiated by FIR
alumina, $d_p = 88\text{--}149\text{ }\mu\text{m}$; silver, $d_p = 74\text{--}149\text{ }\mu\text{m}$; stainless, $d_p = 63\text{--}125\text{ }\mu\text{m}$

Fig. 9. Effect of emissivity of powder materials on T_s of wet granular bed irradiated by FIR
alumina, $d_p = 88\text{--}149\text{ }\mu\text{m}$; silver, $d_p = 74\text{--}149\text{ }\mu\text{m}$; stainless, $d_p = 63\text{--}125\text{ }\mu\text{m}$

emissivities are different from one another, in order to examine the effect of emissivity of the powder materials on the drying characteristic values (constant drying rate and bed temperature). The emissivity of alumina is the highest, and that of silver is the lowest. **Figures 8 and 9**, respectively, show constant drying rate, R_c , and temperature of the granular bed, T_s , irradiated by FIR. In the constant-rate period the temperature is constant through the granular bed. R_c and T_s values vary among the granular beds. R_c and T_s for the alumina bed are the highest among the three granular beds, and those for silver bed are the lowest.

Figure 10 shows the drying characteristic curves for the three samples in the case of convective (hot air) drying. **Figure 11** schematically shows the apparatus for convective drying. The moisture content, ξ , is a volumetric content per unit void volume of the granular bed⁶⁾. The differences of R_c values among the granular beds are negligible in convective drying.

Fig. 10. Drying characteristic curves (convective drying)

Fig. 11. Experimental apparatus for convective drying

Fig. 12. Effect of particle size of powders on R_c of the granular bed irradiated by FIR

However, they are significant in infrared radiation drying, as shown in Fig. 8.

3.2 Effect of particle size of powders

To study the effect of particle size of the powder on R_c , FIR drying was performed with alumina and silver powders of different sizes. **Figure 12** shows the relationship between R_c and q_{ir} . With increase in q_{ir} , R_c of the granular bed with the larger powder becomes higher than that with smaller powder. The differences in R_c between the particle sizes of silver beds of different particle sizes are more significant than those between alumina beds of different particle sizes.

3.3 Effect of spectral distribution of irradiation power

In order to discuss the effect of spectral distribution of irradiation power on R_c , FIR drying and NIR drying of the granular bed were performed by using a FIR heater and a NIR heater respectively. **Figure 13** shows the relationship between R_c and q_{ir} . With increase in q_{ir} , R_c of the granular bed irradiated with the FIR heater becomes higher than that with the NIR heater for both the alumina bed and the silver bed. However, for the stainless bed, R_c of the granular bed irradiated with the FIR heater nearly equals that with the NIR heater.

4. Calculation Results and Discussion

In the model calculation, thermal conductivity, viscosity and density of wet air were estimated from the properties^{9,10,11)} of dry air and of water vapor at the temperature of $(T_a + T_s)/2$.

4.1 Effect of emissivity of powder materials

In Figs. 8 and 9 the experimental results of R_c and T_s respectively are compared with the calculated results, in which the effects of the emissivity of the powder materials on R_c and T_s are indicated. The calculated results estimated by using the present model described above are shown as calc. 1 and those by using the previous model⁸⁾, which takes no account of the spectral distributions of infrared absorption by the granular bed and of multiple reflection between the interfaces of water-air and of water-particle in the second layer, are shown as calc. 2. In calc. 1, the parameter β indicated in Eq. (1) is determined by **Fig. 14**, which shows the influence of β on the dimensionless constant drying rate, ξ , estimated by using the present model.

$$\xi = \frac{R_c(d = \beta d_p)}{R_c(d = d_p)} \quad (16)$$

β may be taken in the range from 0.5 to 1.5. As the influence on β on ξ is negligible, as shown in **Fig. 14**, β is treated as unity. Both calculated results have the same tendencies as do the experimental results. The result of calc. 1 agree with the experimental results more consistently than do the results of calc. 2 for the alumina bed and the silver bed.

The comparisons suggest that the value of q_{in} for alumina bed is the largest among the three kinds of the granular beds and the drying characteristic values become the highest as the emissivity of alumina is the highest among the three kinds of powders.

4.2 Effect of particle size of powders

In **Fig. 12**, the experimental results at constant drying rate are compared with the calculated results of R_c , in which the effect of the particle size of the powder on R_c is indicated. The results of calc. 1 agree with the experimental results consistently. However, the results of calc. 2 do not estimate the effect of the

Fig. 13. Effect of distribution of irradiation power on R_c alumina, $d_p = 88\text{--}149\text{ }\mu\text{m}$; silver, $d_p = 74\text{--}149\text{ }\mu\text{m}$; stainless, $d_p = 63\text{--}125\text{ }\mu\text{m}$

Fig. 14. ξ vs. β . (FIR heater. $q_{ir} = 5.93\text{ kW}\cdot\text{m}^{-2}$ alumina, $d_p = 88\text{--}149\text{ }\mu\text{m}$; silver, $d_p = 74\text{--}149\text{ }\mu\text{m}$; stainless, $d_p = 63\text{--}125\text{ }\mu\text{m}$)

particle size of the powder on R_c accurately, because the spectral distribution and the multiple reflection between the interfaces of water-air and of water-particle in the second layer are not considered. The deviation of the calculated results from the experimental data is reduced by about 8% by using the present model.

Comparison suggests that the values of q_{in} and R_c for the granular bed with the larger powder become higher than those for the bed with the smaller powder because the water layer in the void in the first layer of the granular bed becomes deeper and the absorption energy of irradiation power increases with increase in particle size of the powder.

4.3 Effect of Spectral Distribution of Irradiation Power

In **Fig. 13** the experimental results of R_c of the granular bed irradiated with the FIR heater or the NIR heater are compared with the calculated results, in which the effect of the spectral distribution

of the irradiation power is indicated. Between the experimental data and the results of calc. 1, there are the same tendencies and favourable agreement. However, the results of calc. 2 do not estimate the effect of the spectral distribution of irradiation power on R_c , because the spectral distribution and the multiple reflection between the interfaces of water-air and of water-particle in the second layer are not considered. The deviation of calculated results from experimental data is reduced by about 13% by using the present model.

The emissivity of alumina is high in the region of FIR and low in the region of NIR, as shown in Fig. 1. The absorption coefficient of water⁷⁾ is also high in the region of FIR and low in the region of NIR (Fig. 15). For the alumina bed, it is thus suggested that the values of q_{in} and R_c in the case of far-infrared irradiation are higher than those in the case of near-infrared irradiation.

The emissivity of silver is very low and the spectral distribution is negligible, as shown in Fig. 1. The absorption coefficient of water is high in the region of FIR and low in the region of NIR. For the silver bed, it is thus suggested that the values of q_{in} and R_c in the case of far-infrared irradiation are higher than those in the case of near-infrared irradiation.

The emissivity of stainless steel is high in the region of NIR and low in the region of FIR, as shown in Fig. 1. However, the absorption coefficient of water is high in the region of FIR and low in the region of NIR. Then, for the stainless bed, it is suggested that the values of q_{in} and R_c in the case of far-infrared irradiation are nearly equal to those in the case of near-infrared irradiation.

Concluding Remarks

We examined on the factors influencing the constant drying rate of a wet granular bed irradiated by infrared radiation. As variables, the conditions of the granular bed (emissivity of powder materials and particle size of the powders) and the radiative heat source (spectral distribution of irradiation power) were considered. Infrared radiation drying of the granular bed was performed and the heat transfer model in the constant-rate period was examined. The following results were obtained.

1) The difference in constant drying rate depended upon the emissivity of powder materials, particle size of the powders and spectral distribution of irradiation power.

2) The constant drying rate was calculated by using the model taking account of the spectral distribution of absorption of irradiation power by the granular bed.

3) The calculated results were quantitatively compared with the experimental results, and agreed

Fig. 15. Absorption coefficient of water

with the experimental results more consistently than in the case where no account was taken of the spectral distributions of absorption of irradiation power by the granular bed.

Nomenclature

d	= depth of void in the first layer of the model of a wet granular bed	[—]
d_p	= mean particle size of powder	[m]
e	= void fraction	[—]
h_c	= heat transfer coefficient for natural convection	[W·m ⁻² ·K ⁻¹]
k_m	= mass transfer coefficient for natural convection	[m·s ⁻¹]
q	= heat flux	[W·m ⁻²]
r_a	= external reflectivity of water	[—]
r_i	= internal reflectivity of water	[—]
R	= drying rate	[kg-H ₂ O·m ⁻² ·s ⁻¹]
T	= temperature	[K]
u_H	= velocity of hot air	[m·s ⁻¹]
W_e	= electric power supplied to heater	[W]
Y	= absolute humidity	[kg-H ₂ O/kg-dry air]
α	= absorption coefficient	[m ⁻¹]
β	= defined by eq. (1)	[m]
γ	= latent heat of vaporization	[kJ·kg ⁻¹]
ε	= emissivity	[—]
λ	= wave length	[μm]
ζ	= moisture content-void volume basis of sample	[m ³ -H ₂ O/m ³ -void]
ρ	= density	[kg·m ⁻³]
τ_w	= transmissivity of water layer	[—]
ϕ_2	= effective factor for effective emissivity ($\Phi_2 \varepsilon_p$)	[—]

<Subscripts>

a	= air
abs	= absorption
c	= constant-rate period
conv	= convection
evap	= evaporation
in	= input
ir	= irradiation
out	= output
rad	= radiation
p	= powder material

s	= surface
w	= water
λ	= monochromatic
1	= in the first layer of the wet granular bed
2	= in the second layer of the wet granular bed

<Superscript>

* = saturated

Literature Cited

- 1) Al-Arabi, M. and M. K. El-Riedy: *Int. J. Heat Mass Transfer*, **19**, 1399 (1976).
- 2) Arai, N., S. Takahashi and S. Sugiyama: *Kagaku Kogaku Ronbunshu*, **5**, 471 (1979).
- 3) Chapman, A. J.: "Fundamentals of Heat Transfer", 1st ed., p. 463-467, Macmillan Pub., New York (1986).
- 4) Fujii, T. and H. Imai: *Int. J. Heat Mass Transfer*, **15**, 755 (1972).
- 5) Goldstein, R. J., E. M. Sparrow and D. C. Jones: *Int. J. Heat Mass Transfer*, **16**, 1025 (1973).
- 6) Hasatani, M., Y. Itaya and K. Miura: *Drying '86*, vol. 1, p. 227, Hemisphere Pub., New York (1986).
- 7) Hirota, K.: graduation thesis, Tokyo Univ. of Agric. & Tech. (1988).
- 8) Hirota, K., A. Hashimoto, T. Honda, M. Shimizu and A. Watanabe: *Nippon Shokuhin Kogyo Gakkaishi*, **38**, 136 (1991).
- 9) Kagaku Kogaku Kyokai (ed.): "Kagaku Kogaku Benran", 4th ed., p. 51-59, Maruzen, Tokyo (1978).
- 10) Kagaku Kogaku Kyokai (ed.): "Kagaku Kogaku Benran", 5th ed., p. 84-85, Maruzen, Tokyo (1988).
- 11) Kagaku Kogaku Kyokai (ed.): "Kagaku Kogaku Benran", 5th ed., p. 93, Maruzen, Tokyo (1988).
- 12) Kawasaki, M.: "Ensekigaisen Riyo no Saishin Gizyutsu", Shimizu, M. ed., 1st ed, p. 34. Kogyo Gizyutsukai, Tokyo (1987).
- 13) Nippon Kikai Gakkai (ed.): "Ryutai no Netsu Busseichi-Shu" ("JSME Data Book: Thermophysical Properties of Fluid"), p. 505, Maruzen, Tokyo (1983).
- 14) Nippon Dennetsu Kyokai (ed.): "En-sekigaisen no Riron to Jissai", 1st ed., p. 8, Ohm sha, Tokyo (1991).
- 15) Nishimura, M., M. Kuraishi, Y. Bando and H. Kojima: *Kagaku Kogaku Ronbunshu*, **10**, 124 (1984).
- 16) Nishimura, M., M. Kuraishi and Y. Bando: *Kagaku Kogaku Ronbunshu*, **9**, 148 (1983).
- 17) Yagi, S. and D. Kunii: *Kagaku Kikai*, **15**, 108 (1951).
- 18) Yagi, S., D. Kunii and S. Katsuki: *Kagaku Kikai*, **15**, 117 (1951).