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DRYING OF FLUIDIZED MATERIALS IN A CENTRIFUGAL FLUIDIZED BED

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Abstract—Drying characteristics of the fluidized food materials such as rice, potato and carrot have been investigated in a centrifugal fluidized bed whose effective length and diameter have been 0.2 m and 0.1 m, respectively. The effects of air velocity and initial moisture content on the hydrodynamics and drying rate have been determined. The pressure drop has exhibited a maximum in the relatively thicker bed, while it has showed a plateau in the relatively thinner bed, with an increase in the air velocity. The drying rate has been increased with increases in the initial moisture content of the materials and air velocity. The variation of drying rate with respect to the moisture content has been almost linear at the falling rate period, and it has been well correlated by means of the rotational power acting on the bed.

Key words: Drying, Centrifugal Fluidized Beds, Food Materials

INTRODUCTION

Fluidized beds have been employed for various kinds of processes in the industries owing to their several advantages such as simplicity of design, intimate gas-to-particle contact, uniform particle exposure without mechanical agitation etc. However, the application of the fluidized beds has been limited, because they have to be operated at the gas velocity in the range between the minimum fluidization velocity and the terminal velocity of the particles, which are usually determined from the properties of the fluidized particles.

The centrifugal fluidized beds can overcome the limitations of the vertical conventional fluidized bed by adjusting the centrifugal force or rotating speed, which can increase apparently the velocity or density of gas in the bed. The centrifugal fluidized bed can also allow the smooth and homogeneous fluidization in the bed at any desired gas velocity, since the centrifugal force let the bed operating parameters set independently of the physical properties of the materials being treated [Fan, 1978; Kroger et al., 1979; Chen, 1987].

Various kinds of industries such as chemical, agricultural, food, pharmaceutical and biochemical industries need the more efficient drying process, because the drying processes are often appeared to be time-consuming, troublesome and sometimes critical. Moreover, for the drying of thermally-weak materials any kind of heating including mixing with hot gas cannot be used to prevent the materials from reaction or decomposition during drying. It could be a solution for the drying of those materials to adopt the centrifugal fluidized bed.

Fan [1978] pointed out that the centrifugal fluidized bed could be used efficiently for the combustion of particles. A few investigators [Kroger et al., 1979; Chen, 1987; Takahashi, 1984; Fan et al., 1985] have studied the hydrodynamic characteristics of the centrifugal fluidized bed including the pressure drop and critical or minimum fluidization velocity in the bed of centrifugal field. However, the results of their study have not been consistent; some of them [Kroger et al., 1979; Chen, 1987] have found that the pressure drop in the bed has showed a plateau, but others [Takahashi, 1984; Fan et al., 1985] have observed that it has exhibited a maximum value, with an increase in the gas velocity at a constant centrifugal force field.

In the present study, the drying characteristics of the fluidized materials such as rice, potato and carrot have been investigated in a centrifugal fluidized bed. The effects of gas velocity and initial moisture content on the drying rate and pressure drop have been determined. The variation of drying rate has been correlated with the rotational power acting on the bed, which is defined as functions of the rotational speed, bed thickness, column radius and mass flow rate of gas.

EXPERIMENT

Experiments were carried out in a centrifugal fluidized-bed dryer whose effective length and diameter were 0.2 m and 0.1 m, respectively, as can be seen in Fig. 1. Compressed and filtered air was fed to the bed through the distributor at the wall of the horizontal column, and its velocity was measured by two calibrated rotameters. The tubular distributor box whose diameter was 0.15 m was installed at the outside of the horizontal fluidized bed coaxially for the even distribution of the air injected to the column. The portion of holes in the distributor was 55% of the distributor area, and 400 mesh stainless steel screen was attached at the inside of the distributor to prevent the powders from leakage during dried from the fluidized bed. The fluidized bed was rotated by means of the DC motor connected to the central axis of the column, whose rotational speed was controlled by the speed control system connected to the DC motor. The sections of feed input and product output as well as inlet and outlet of the air were separated from the moving section by means of mechanical sealing. The air from the centrifugal fluidized bed was vented

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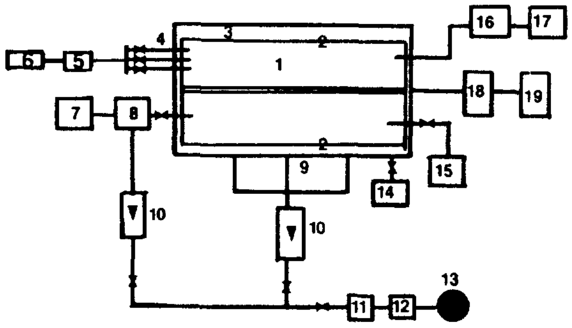

Fig. 1. Schematic diagram of experimental apparatus.

1. Column	11. Thermocouple
2. Distributor	12. Filter & Regulator
3. Distributor box	13. Compressor
4. Pressure tap	14. Drain
5. Pressure sensor & transducer	15. Product outlet
6. Recording system	16. Cyclone
7. Hopper	17. Bag filter
8. Feeder	18. DC motor
9. Air inlet	19. Speed controller
10. Rotameter	

to atmosphere through two cyclones and a bag filter.

The feed materials were rice, carrot and potato whose mean density was 1350, 1200 and 1250 (kg/m^3), respectively, and the shape of them was either prolate (rice) or cubic (carrot and potato). The range of initial moisture content of the materials was 0.35-0.58 (kg/kg solid) and the gas velocity was varied from 3.94 to 6.29 (m/s). To measure the moisture content of the materials being dried, sampling of the materials was made at the time interval of 5 or 10 min after starting the drying. The temperature and pressure of the experimental condition were 25℃ and 1 atm, respectively. The rotational speed of the centrifugal fluidized bed was in the range of 31.4-71.4 rad/s. The average relative humidity of the air was 20%. The minimun fluidization velocity of the materials fluidized in the bed was in the range of 0.8-1.25 (m/s) depending on the experimental conditions. The physical properties of the feed materials and the experimental conditions were summarized in Table 1.

The pressure drop in the bed was measured by means of pressure sensor (Copel Electronics, Semiconductor type) and its detection system, which were connected to the pressure taps located at one side of the column. The moisture content of the material being dried was measured by a micro moisture content measurement system (Coulometer).

RESULTS AND DISCUSSION

1. Pressure Drop

As in the conventional vertical fluidized beds, the minimun fluidization velocity in the centrifugal fluidized beds can also be determined from the relation between the pressure drop in the bed and the gas velocity. From the experimental results of Kroger et al. [1979] and Chen [1987], the pressure drop in the centrifugal fluidized beds increases gradually with an increase in the gas velocity within the relatively low gas velocity range, but it approaches to a almost constant value with a further increase in the gas velocity showing a plateau. However, Takahashi et al. [1984] and Fan et al. [1985] observed that the pressure drop in the centrifugal fluidized beds attained its maximum value with an increase in the gas velocity.

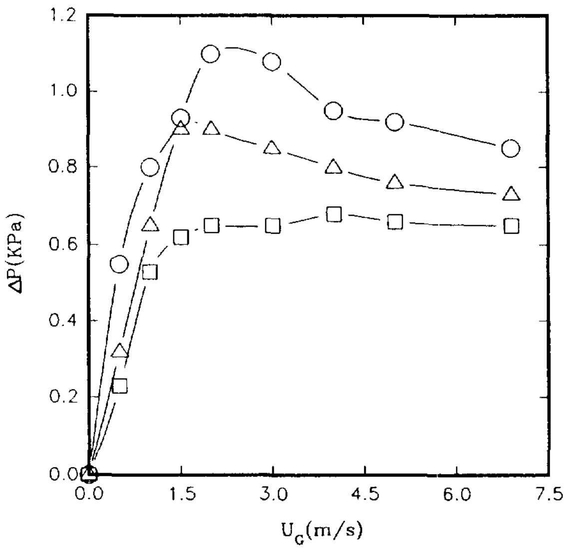

Fig. 2. Pressure drop with the variation of air velocity in the centrifugal fluidized bed (Rice, N=41.7 rad/s).

		○	△	□
W (kg)	:	0.75	0.50	0.40
X (kg/kg solid)	:	0.43	0.35	0.35
L (m)	:	0.03	0.02	0.01

From the results of this study, both of these two kinds of trend of the pressure drop variation could be possible, since the pressure drop would be strongly dependent upon the thickness of the bed and the radius of the dryer [Kao et al., 1987; Kang et al., 1994]. The existence of an interface between the fluidized-bed region and the packed-bed region in centrifugal fluidized beds has been verified by Kao et al. [1987] who pointed out that the trend of ΔP variation in the thick bed can be influenced by the grade of partial fluidization. Fig. 2 illustrates the total pressure drop in the centrifugal fluidized bed of rice with the variation of air velocity. Note in this figure that the pressure drop exhibits a maximum value when the bed thickness is 2 or 3 cm, while it shows a plateau when the bed thickness is 1 cm, with an increase in the air velocity. This can be due to the partial fluidization which could be significant in the relatively thick centrifugal fluidized beds [Kao et al., 1987; Kang et al., 1994]. The minimum fluidization velocity of the materials in the bed has been deter-

Table 1. Experimental condition

Material	Size (×10^3, m)	Shape	Mean density (kg/m^3)	Initial moisture content (kg H_2O/kg Solid)	Gas velocity (m/s)	Loading (kg)
Rice	5×3.3	Prolate (spheroid)	1350	0.35-0.52	3.94-6.29	0.35-0.75
Carrot	5×5×5	Cubic	1200	0.43-0.58	3.94-6.29	0.35-0.75
Potato	5×5×5	Cubic	1250	0.35-0.52	3.94-6.29	0.35-0.75

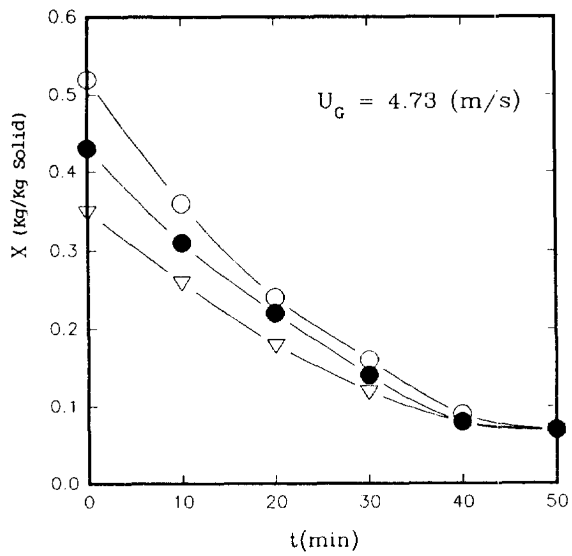

Fig. 3. Moisture content of the materials with the variation of drying time (Potato, N=41.7 rad/s, U_G=4.73 m/s).

	○	●	▽
X_0 (kg/kg solid) :	0.52	0.43	0.35

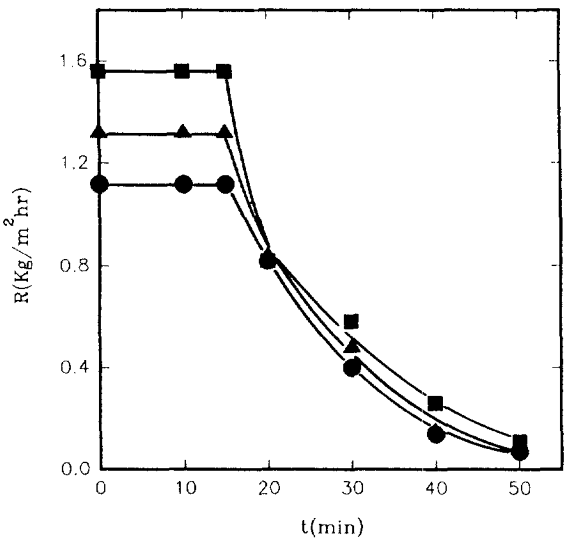

Fig. 4. Drying rate with the variation of drying time in the centrifugal fluidized bed (Carrot, N=47.1 rad/s, X_0=0.58).

	●	▲	■
U_G (m/s) :	3.94	4.73	6.29

mined as the gas velocity where the pressure drop exhibits its maximum value or it starts to maintain at a constant value.

2. Drying Rate

Fig. 3 illustrates the variations of moisture content of the potato with an increase in the drying time. In this figure, the moisture content decreases noticeably within early 15 minutes, and then it decreases gradually with drying time. This can be explained that the removal of moisture from the wet materials can occur at the vicinity of the surface of the material at the early stage of drying, however, it takes time for the moisture interior of the material has to be transferred to the surface of it by diffusion or other mechanism, since the resistance of moisture transfer could increase with drying time.

The drying rate which can be generally defined as Eq. (1) has been obtained from the relation between the moisture content of the material and the drying time [Lee, 1994; Mujumdar, 1987; Bird et al., 1960].

$$R=-\frac{1}{A}\frac{dX}{dt} \tag{1}$$

The variation of drying rate of the pieces of carrot with the drying time can be seen in Fig. 4, where the drying rate has remained constant for about early 15 minutes and then it has decreased profoundly, with an increase in the drying time. It can be noted in this figure that the higher the air velocity the greater the drying rate in the centrifugal fluidized bed.

Typical drying curves of the potato and carrot can be seen in Fig. 5 and 6, respectively, at a given rotational speed and air velocity. Note in these figures that the drying rate has exhibited the greater value with an increase in the initial moisture content of the feed materials in the constant drying rate period. The reason can be explained that the amount of moisture which is entrapped either at the surface or in the vicinity of the surface can increase with an increase in the initial moisture content of the materials. Since the resistance for the evaporation of the moisture at the surface is much lower than that of the moisture holded

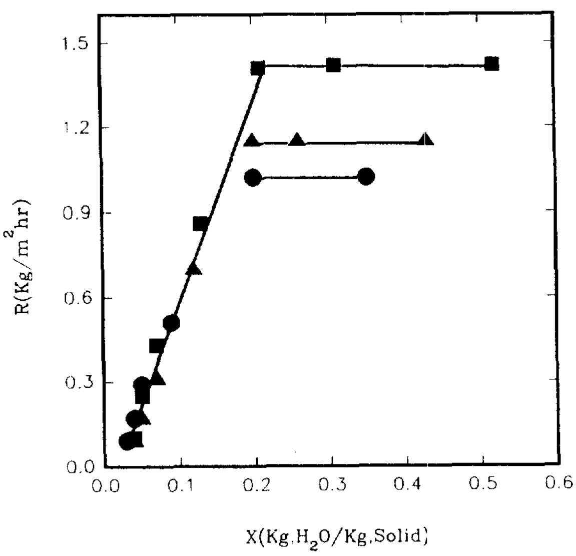

Fig. 5. Drying curve of potato in the centrifugal fluidized bed (U_G=6.29 m/s, N=52.3 rad/s).

	●	△	■
X_0 (kg/kg solid) :	0.35	0.43	0.52

interior of the material [Lee, 1994; Mujumdar, 1987; Bird et al., 1960], the escaping of the moisture from the surface of the material is somewhat easier than that from the interior of the material. The driving force on the drying rate of the materials is the difference between the moisture content and the critical moisture content in the constant drying rate period, while the driving force in the falling rate period is the difference bewteen the moisture content and the equilibrium one. Since the driving force of the more wet material is larger than that of the less one, the drying rate of the former shows higher value than that of the latter, in the constant dryirfg rate period. When the moisture content of the material approaches to the critical one, further drying

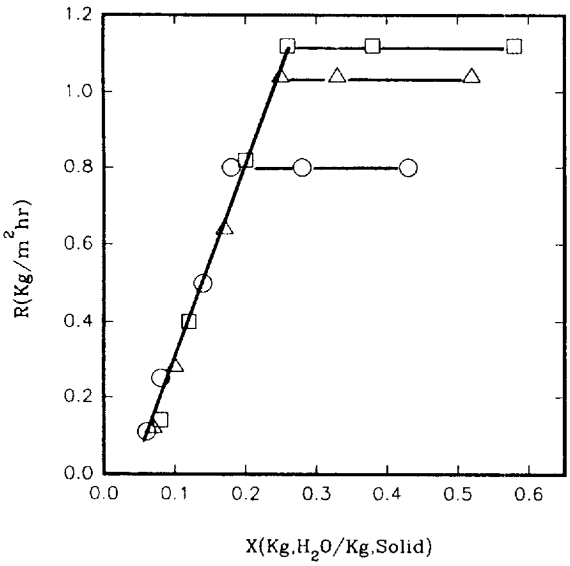

Fig. 6. Drying curve of carrot in the centrifugal fluidized bed (U_G= 3.94 m/s, N=52.3 rad/s).

	○	△	□
X_0 (kg/kg solid) :	0.43	0.52	0.58

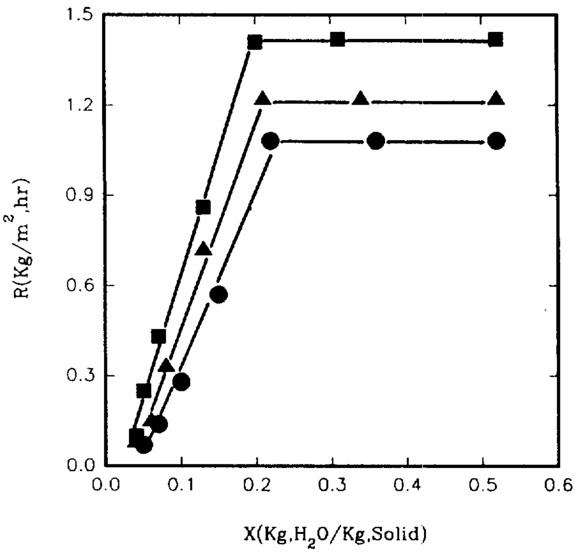

Fig. 7. Drying curve of potato in the centrifugal fluidized bed (X_o= 0.52 m/s, N=41.7 rad/s).

	●	▲	■
U_G (m/s) :	3.94	4.73	6.29

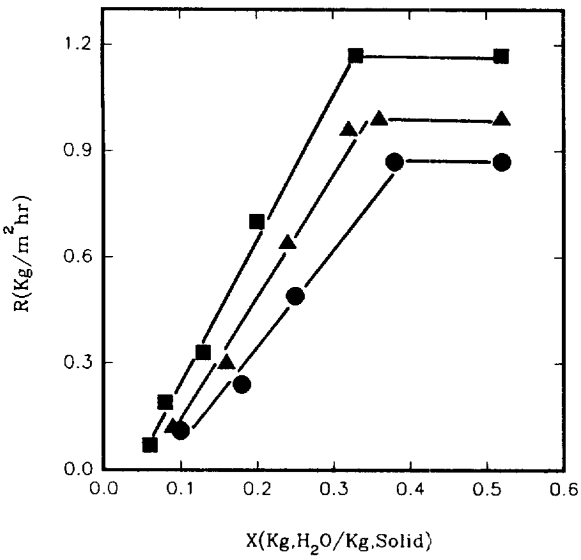

Fig. 8. Drying curve of rice in the centrifugal fluidized bed (X_o=0.52 m/s, N=52.3 rad/s).

	●	▲	■
U_G (m/s) :	3.94	4.73	6.29

causes dry spots to appear on the surface of the material. However, the drying rate has been computed to the overall solid surface area, thus the drying rate can fall although the rate per unit wet solid surface area remains constant [Mujumdar, 1987]. And the high level of the drying rate can not be maintained with the progress of drying, especially in the case of more wet materials. Thus, the drying rate tends to fall down more easily in those materials (Figs. 5 and 6).

In the falling drying rate period, the decreasing trend of the drying rate with a decrease in the moisture content of the fluidized material has been almost linear and independent the initial moisture content.

Effects of air velocity on the drying rate of the fluidized materials can be seen in Figs. 7 & 8. Fig. 7 is the drying curve of the rice, and Fig. 8 is that of the potato. In both figures, the slope of the decrease of the drying rate with a decrease in the moisture content of the material, in the falling rate period, has become steeper with an increase in the air velocity in the centrifugal fluidized bed. This can be due to that the drying efficiency of the material is relatively high at the relatively higher air velocity. Actually, the drying rate shows the relatively higher value with an increase in the air velocity either at the constant or falling rate period when the initial moisture content of the material has been constant. At a constant rotational speed, the increase of air velocity in the centrifugal fluidized bed can result in the increases both in the amount of air to carry out the moisture from the material and in the bed porosity owing to increase in the drag force on the fluidized materials, and thus increase in the contacting efficiency between the air and the materials being dried. However, the increase in the rotational speed of the centrifugal fluidized bed results in the decrease of the bed porosity due to the increase in the centrifugal force on the fluidized materials, thus consequently results in the decrease in the drying efficiency and drying rate of the materials, when the gas velocity has not been sufficient.

3. Correlation

Since the drying rate decreases linearly with a decrease in the moisture content of the fluidized materials, it can be easily correlated with the operating variables such as rotational speed of the centrifugal fluidized bed, bed thickness, bed diamater, air velocity etc. The fluidized materials in the centrifugal field are forced into the annular region at the circumference of the bed, thus, the pressure drop, bed porosity, velocity distribution of gas and angular momentum in the annular region have been important factors for determining the performance of the centrifugal fluidized beds. The rotational power can be used to represent these factors synthetically and effectively, since it does not depent on the dimension and capacity of the device [Mujumdar, 1987; Bird

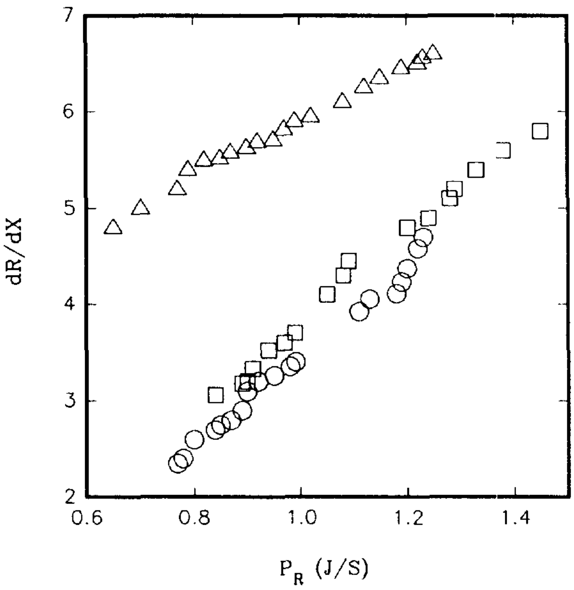

Fig. 9. Relation between the dR/dX and the rotational power in the centrifugal fluidized bed.

		●	▲	■
material	:	rice	potato	carrot

et al., 1960; Levy et al., 1976]. The rotational power can be defined as the multiplication of the torque needed to rotate the fluidized bed by the angular velocity [Bird et al., 1960; Levy et al., 1976]. The torque for the rotation of the bed can be equal to the exit angular momentum of the fluid as

$$\tau=\int ru_t\rho u_Z \ 2\pi r \ dr \tag{2}$$

Evaluating the Eq. (2) over the exit plane of the fluidized bed and multiplying by angular velocity, the rotational power can be written as

$$P_R=N^2 \ r_o \ r_i\dot{m} \tag{3}$$

, where r_o and r_i are the radius of the fluidized bed and the inner surface of the bed, respectively, and $\dot{m}$ is the mass flow rate of the air entering the bed.

As can be seen in Fig. 9, the slope of the drying rate with respect to the moisture content of the material, dR/dx, increases with an increase in the rotational power, since the rotational power is directly related to the fluidizing condition of the bed materials in the annular region. The variation of dR/dx has been correlated with the rotational power as

$$\frac{dR}{dX}=3.42 \ P_R^{1.20} \quad \text{for rice} \tag{4}$$

$$\frac{dR}{dX}=3.80P_R^{1.25} \quad \text{for potato} \tag{5}$$

$$\frac{dR}{dX}=5.93P_R^{0.45} \quad \text{for carrot} \tag{6}$$

The correlation coefficient of the Eq. (4), (5) or (6) was 0.932, 0.926, and 0.918, respectively. The drying rate can also be obtained from the integration of Eq. (4)-(6) with the suitable boundary condition of initial moisture content.

CONCLUSION

Drying of thermally-sensitive food materials such as rice, potato and carrot has been successfully performed by adopting the centrifugal fluidized bed. The variation of pressure drop with the air velocity has been dependent upon the amount of materials loaded in the bed; the pressure drop has exhibited a maximum value when the thickness of bed materials has been increased, but it has showed a plateau when the bed thickness has been thin, with an increase in the air velocity.

The drying rate has been increased with increases in the initial moisture content of the materials and air velocity. The variation of drying rate with respect to the moisture content has been almost linear at the falling rate period, and it has been well correlated with the rotational power acting on the bed.

ACKNOWLEDGEMENT

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NOMENCLATURE

A	: surface area [m^2]
L	: bed thickness [m]
$\dot{m}$	: mass flow rate of air [kg/sec]
N	: rotational speed [rad/sec]
ΔP	: pressure drop in the bed [Pa]
P_R	: rotational power [J/sec]
R	: drying rate [kg/m^{2}hr]
r	: distance in the radial direction [m]
r_i	: distance from the center to the inner surface of the bed [m]
r_o	: radius of the bed [m]
t	: drying time [sec]
U_G	: air velocity [m/s]
U_T	: tangential component of velocity [m/s]
U_Z	: axial component of velocity [m/s]
W	: feed loading [kg]
X	: moisture content of the material [kg H_2O/kg solid]
X_0	: initial moisture content of the material [kg H_2O/kg solid]

Greek Letters

τ	: torque [J/rad]
ρ	: density of the air [kg/m^3]

REFERENCES

Bird, R. B., Stewart, W. E. and Lightfoot, E. N., "Transport Phenomena", John Wiley & Sons, Inc., N.Y. (1960).

Chen, Y. M., "Fundamentals of a Centrifugal Fluidized Bed", *AIChE J.*, **33**, 722 (1987).

Fan, L. T., "Fluidized Bed Combustion in Centrifugal Field", *Energy Commun.*, **4**, 509 (1978).

Fan, L. T., Chang, C. C., Yu, Y. S., Takahashi, T. and Tanaka, Z., "Incipient Fluidization Condition for a Centrifugal Fluidized Bed", *AIChE J.*, **31**, 999 (1985).

Kao, J., Pfeffer, R. and Tardos, G. I., "On Partial Fluidization in Rotating Fluidized Beds", *AIChE J.*, **33**, 858 (1987).

Kang, Y., Shim, J. S., Choi, M. J., Lee, K. W. and Kim, S. D., "Drying of Thermally-Weak Powder in a Centrifugal Fluidized-Bed Dryer", Proc. 4th Asian Conf. on Fluidized Beds and Three-

Phase Reactors, Fukuoka, Japan, November 28-30, 67 (1994).
Kroger, D. G., Levy, E. K. and Chen, J. C., "Flow Characteristics in Packed and Fluidized Rotating Beds", *Powder Technol.*, **24**, 9 (1979).
Lee, D. H., "Drying Characteristics of Fine Powders in a Media Fluidized Bed", Ph D. Thesis, KAIST (1994).
Levy, E. K., Dodge, C. and Chen, J., "Parametric Analysis of a Centrifugal Fluidized Bed Coal Combustor", Proceeding of the ASME-AIChE Heat Transfer Conference, St. Louis, August 9-11 (1976).
Mujumdar, A. S., Handbook of Industrial Drying, Marcel Dekker, Inc., N.Y. (1987).
Takahashi, T., Tanaka, Z., Itoshima, A. and Fan, L. T., "Performance of a Rotating Fluidized Bed", *J. Chem. Eng. Japan*, **17**, 333 (1984).