

Studies on Through Flow Rotary Dryer

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The drying procedure in the through flow rotary dryer was investigated by experimental equipment. From the drying rate, the heat transfer capacity coefficients of the through flow rotary dryer were calculated. The heat transfer capacity coefficients based on the dryer volume were 500–1800 (kcal/hr m³-dryer vol. °C) which were large values as compared with those generally obtained from rotary dryers. The experimental correlations of the heat transfer capacity coefficients against the Reynolds number were obtained by the equation $h_a D_p = 0.476 R_e^{0.8}$.

1. Introduction

Rotary dryer as commercial equipment have been commonly used by process industries to dry granular free flowing solids because of their large capacity and of their flexibility of performance. Heat and mass transfer between gas and materials in the rotary dryer have been studied by many investigators. The most notable studies on the experimental aspects of dryer performance reported are those of Miller, Smith and Schutte⁵⁾, Prutton, Miller and Schutte⁶⁾, Friedman and Marshall^{1), 2)}, and Shinohara⁹⁾. Friedman and Marshall correlated the data of overall heat capacity coefficients measured by experimental equipment as the function of the diameter of dryer, and the mass velocity of gas. One of the authors, R. Toei⁸⁾ summarized the data of the many investigators which have been reported and proposed an empirical equation for the heat transfer coefficients as the functions of the diameter of dryer, the hold up of materials and the mass velocity of gas. However, the data obtained from the commercial equipment does not indicate the heat transfer capacity coefficients over 200 (kcal/hr. m³-dryer vol. °C) and this is a weak point of the rotary dryer. To overcome this weak point, the combinations of the through flow method and the rotary action are considered and are used as the Roto Louvre dryer⁷⁾. Many studies of the heat transfer capa-

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city coefficients in the rotary dryer have been reported and also the heat and mass transfer between fluid and particles in a packed bed or the fluidizing bed are studied by many investigators. However, the available data of heat and mass transfer between gas and materials being agitated by rotary action can not be found. In this report, the through flow drying rate of materials agitated by rotary action was measured and the data of heat transfer capacity coefficients of the through flow rotary dryer were correlated.

2. Experimental apparatus and procedure

The experimental apparatus consisted of rotary cylinder, table feeder, air heater, air blower and measuring instruments of temperature, static pressure and air velocity as shown in Fig. 1. The details of the dryer are illustrated in Fig. 2. (a) (b). A simple mechanical method is employed to seal the rota-

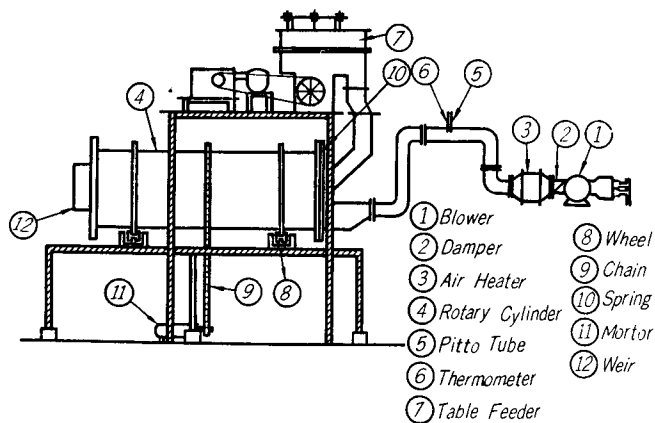


Fig. 1. Experimental apparatus of through flow rotary dryer.

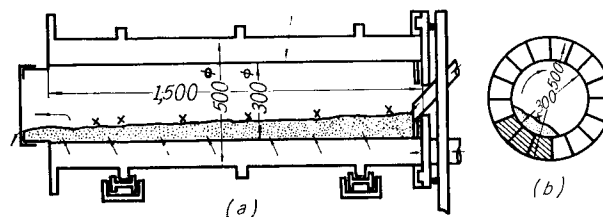


Fig. 2 (a) (b). Details of rotary cylinder.

ting cylinder at the inlet where the hot air and materials are admitted. The cylinder is doubled and has the inside diameter of 0.3m and the outside diameter of 0.5m and the length of 1.5m. The inside cylinder is made of perforated plate with a hole of 2mm from which the hot air is blown and is

covered with a wire net of 50 mesh. The annular space between the inside and outside cylinder is divided into sixteen sections and hot air enters only through the three sections directly underneath the material. Exhaust gases are removed from the product-discharge end of the rotating cylinder. Rotation rate of cylinder was 6 r.p.m. through all the runs and was enough to keep the material in continuous agitation and convey them through the dryer. The dryer was maintained horizontally and was insulated to prevent heat loss. The spherical particles of activated alumina (mean surface diameter $D_p = 4.55$ mm, 1.40 mm) and iron slag ($D_p = 0.312$ mm) were used as experimental materials.

At first the experimental equipment is preheated by hot air with no loading and then the wetted material is charged from the table feeder and drying operations are started. After the process of drying reached a steady state, the measurements were begun. About 1 hr was required to bring it up to steady operating conditions. The measurements were performed as follows:

- (1) The velocity of the air was measured by pitot tube.
- (2) The temperature of the air was measured at the inlet of dryer by a thermocouple.
- (3) Inserting the thermocouple fixed to the top of a bar of about 2 m length into the dryer, the temperatures of the exhaust air through the bed were measured at several locations on the center line of the material bed at the distance of 30, 40, 60, 80, 100, 120 cm from the discharge end of the dryer. These are indicated by the mark X in Fig. 2 (a) (b).

After the measurements described above were performed, the operation of the dryer was stopped and then the temperature of the bed of material was also measured by inserting the thermocouple into the bed of material at several points along the dryer length and the material was sampled to measure moisture content at the same point. It was very difficult to obtain the true temperature of the material, but the temperature of material bed measured as described above could be considered as having a similar change as the true temperature of the material. Finally, the material maintained in the dryer was discharged and weighed to estimate the hold up to materials in the dryer. Moisture contents of the materials sampled along the dryer length, of the feed and of the product were determined by drying each of three weighed samples overnight in an oven maintained at $105 \pm 2^\circ\text{C}$ and determining the loss in weight of the samples and averaging the values obtained from the three samples. The drying tests were performed in the range of air temperature

from 60 to 120°C, air velocity from 390 to 700 kg/hr, feed rate from 18 to 55 kg/hr and the height of weir at the discharge end of materials 5, 6, and 7 cm.

3. Experimental results

From the experimental procedure described above, drying curves were obtained as the relation of the reduced water contents and the temperature of air and bed of material versus the dryer length or the retention time. An example of a drying curve obtained with the activated alumina ($D_p = 4.55$ mm) was illustrated in Fig. 3. The water content does not decrease from the inlet to about 0.5 m length of the dryer and then decrease straight-forwardly to the end of the dryer. From this observation, the range from the inlet to about 0.5 m length of the dryer are regarded as the preheating zone and the range

following that is considered the constant drying rate zone. The temperature of the material bed during the constant drying rate period indicates a constant temperature higher than the wet bulb temperature of the inlet air. As mentioned above, this temperature is not the true temperature of the material but is that measured by inserting the thermocouple into the material bed, so it is seen to be natural that the temperature of the bed would be higher than the wet bulb temperature of the inlet air. As it was experimentally known that the activated alumina which has a moisture content greater than 20 percent will be in the constant drying rate period⁴⁾, it seems to be correct that the temperature of material should be the wet bulb temperature of inlet air. The experimental data are summarized in Table 1 and 2 with the calculated value.

4. Heat transfer capacity coefficients

In order to calculate the heat transfer capacity coefficients of a dryer, the gas flow rate during the constant drying rate period zone and the mean exhaust gas temperature through the bed must be estimated. Total gas flow rate G_0 is known, but during the preheating period the gas flow rate per unit area is smaller than that during the constant drying rate period because the materials are wet. Therefore, the fraction of gas flow rate at each zone must

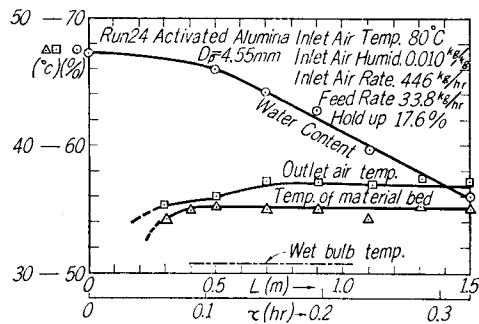


Fig. 3. Experimental curve of drying.

Table 1. Experimental Data of Drying of Activated Alumina.

	Run	G_0 (kg/hr)	F_0 (kg/hr)	t_1 (°C)	H_f (cm)	X' (kg)	X (%)	τ (hr)	ha_0	G_{I0} (kg/hr)	G_{II0} (kg/hr)	G_{II} (kg/hrm ²)	Re	ha	haD_P
$D_P=4.55$ mm	22	609	35.4	92.0	6	10.85	17.2	0.307	4840	211	398	2260	111	4330	15.35
	23	597	34.9	109.8	6	11.15	17.7	0.319	4150	73.5	523.5	2700	133	4660	16.5
	24	447	33.8	74.1	6	11.10	17.6	0.238	4640	72	374	2060	104	5390	19.1
	25	612	41.7	92.0	6	11.45	18.2	0.283	7700	105	507	2740	136	6530	23.2
	26	544	36.4	49.3	6	11.50	18.2	0.318	5740	112	432	2340	113	8250	29.3
	27	616	32.3	71.75	6	10.9	17.3	0.328	3820	116	525	2710	169	4280	19.5
	28	606	54.1	91.3	6	12.3	19.5	0.224	6710	105	501	3160	218	7860	35.8
	29	467	52.5	91.8	6	11.6	18.4	0.221	4440	103	364	2580	163	5660	25.8
	30	398	51.5	91.7	6	11.8	18.7	0.229	4410	103	295	2100	134	5770	26.3
	31	516	48.2	91.2	6	13.4	21.2	0.278	3840	116	400	2270	145	4080	18.5
	32	609	48.0	92.3	5	8.24	13.0	0.171	8890	114	495	3520	224	8970	40.8
	34	594	26.4	90.8	6	9.5	14.1	0.360	5220	94	500	2840	179	6280	28.6
	35	599	52.0	91.4	6	11.35	18.1	0.218	5810	135	464	2930	188	8400	38.3
	36	432	50.3	91.4	6	11.7	18.6	0.233	5460	280	152	1440	91.7	4070	18.5
$D_P=1.40$ mm	102	605	24.0	74.2	6	10.4	14.2	0.434	4850	89	516	2930	55.9	5760	8.08
	103	585	24.4	109.6	6	10.85	14.8	0.426	4450	191	394	2800	50.1	5600	7.85
	104	511	24.4	110.1	6	10.5	14.4	0.430	4030	217	294	1670	28.7	3140	5.65
	105	421	24.4	110.4	6	10.6	14.5	0.435	3530	203	217	1230	22.0	2220	4.94
	106	392	25.5	109.4	6	9.96	13.6	0.447	4150	169	223	1580	28.5	4150	5.82
	107	570	23.5	110.7	7	11.8	16.1	0.502	3940	159	411	2340	42.9	4250	6.37
	108	519	23.9	110.7	5	7.25	9.9	0.303	5800	189	350	2210	39.6	6500	9.12
	109	520	36.4	110.4	6	10.32	14.1	0.284	5240	182	338	2120	38.1	6670	9.35
	110	523	42.8	109.3	6	11.40	15.7	0.267	4850	177	362	2530	49.0	6990	9.78

Table 2. Experimental Data of Drying of Iron Slag.

Run	G_0 (kg/hr)	F_0 (kg/hr)	t_1 (°C)	H_f (cm)	X' (kg)	X (%)	τ (min)	G_{II} (kg/hrm ²)	Re	ha	haD_P
2	499	44	103	6	13.3	9.8	18.3	2820	12.45	13500	4.21
3	452	45.6	101.1	6	12.7	9.3	16.8	2820	12.45	17500	5.45
4	568	38.2	103.6	6	12.1	8.8	19.0	3210	14.18	14700	4.58
6	572	76	100	6	14.6	10.6	11.5	4070	17.96	19250	5.98
9	573	55.5	102.5	5	9.55	5.92	10.3	3240	14.2	16400	5.11

be estimated from experimental data under some assumptions. It is assumed that the profile of temperature distribution of exhaust gas through the bed at the cross section of the dryer may be shown as in Fig. 4. It is reasonable to assume that this distribution may be held throughout the preheating zone (I) and the constant drying rate zone (II). We have assumed the minimum temperatures of exhaust gas t_{2I} and t_{2II} as shown on Fig. 4, so $\Delta t_{I \max}$ and $\Delta t_{II \max}$ are obtained. The $\Delta t_{I \text{ave}}$ and $\Delta t_{II \text{ave}}$ may be calculated by the following relations based on the assumption described above:

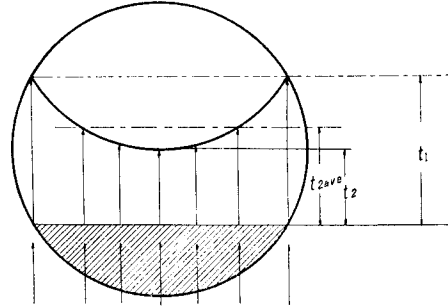


Fig. 4. Distribution of outlet air temp.

$$\frac{(t_1 - t_{2I})}{(t_1 - t_{2I \text{ave}})} = \frac{\Delta t_{I \max}}{\Delta t_{I \text{ave}}} = \frac{(t_1 - t_{2II})}{(t_1 - t_{2II \text{ave}})} = \frac{\Delta t_{II \max}}{\Delta t_{II \text{ave}}} \quad (1)$$

Showing the heat transferred from the hot air to the materials during the preheating zone by q_I (kcal/hr) and the heat transferred during the constant drying rate period by q_{II} (kcal/hr) and the mass velocities of the air in each zone by G_{I0} and G_{II0} (kg/hr), heat balances of each zone are as follow:

$$q_I = F_0(C_s + w_1)(t_m - t_{mI}) + F_0(w_1 - w'_1)r_{wI} = G_0 C_H (\Delta t_I)_{\text{ave}} \quad (2)$$

$$q_{II} = F_0(w_1 - w_2)r_{mII} = G_{II0} C_H (\Delta t_{II})_{\text{ave}} \quad (3)$$

$$G_0 = G_{I0} + G_{II0} \quad (4)$$

$$\frac{G_{I0}}{G_{II0}} = \frac{q_I}{q_{II}} \cdot \frac{\Delta t_{II \text{ave}}}{\Delta t_{I \text{ave}}} = \frac{q_I}{q_{II}} \cdot \frac{\Delta t_{II \max}}{\Delta t_{I \max}} \quad (5)$$

By solving equations (4) and (5) simultaneously, G_{I0} and G_{II0} can be calculated and the average temperature of the exhaust air $t_{2I \text{ave}}$ and $t_{2II \text{ave}}$ also can be calculated from the values of G_{I0} and G_{II0} . Where w' is the water content at the beginning of the constant drying rate period and r_{wI} and r_{wII} are the latent heat in the each zone. The heat transfer capacity coefficients during the constant drying rate period are defined by the following equations:

$$ha = \frac{q_{II}}{(\Delta t)_{Im} V_{pII}} \quad (6)$$

$$ha_0 = \frac{q_{II}}{(\Delta t)_{Im} V_{pII}} \quad (7)$$

Where V_{pII} is the bed volume and ha_0 is the heat transfer capacity coefficient

based on the dryer volume V which is conveniently used to obtain the dryer volume though it has no physical meaning. Letting the hold-up of materials in the dryer be X fraction, the following relation between ha and ha_0 is found.

$$ha = \frac{ha_0}{X} \quad (8)$$

To calculate the driving force $(\Delta t)_{im}$, it was assumed that the surface temperature of material was the wet bulb temperature of the inlet air as described before. The Reynolds number based on the area of the inside cylinder from which the hot air is blown was calculated from the value of $G_{II} = \frac{G_{II0}}{A}$ (kg/hr m²), that is:

$$Re = \frac{D_p G_{II}}{\mu} \quad (9)$$

The heat transfer capacity coefficients calculated as described above were plotted against the Reynolds number defined by equation (9) as shown in Fig. 5. It is recognized that the plotting of the heat transfer capacity coefficients versus Reynolds number are on the parallel straight lines of which the diameters of the particles are the parameter. The effects of the feed rate and the height of the weir to the heat transfer capacity coefficients could not be recognized. From Fig. 5, it is estimated that ha is inversely proportional to the particle diameter, therefore plotting haD_p against the Reynolds number, a good correlation was obtained as shown in Fig. 6. The experimental equation of the heat transfer capacity coefficients were finally expressed by the following equation:

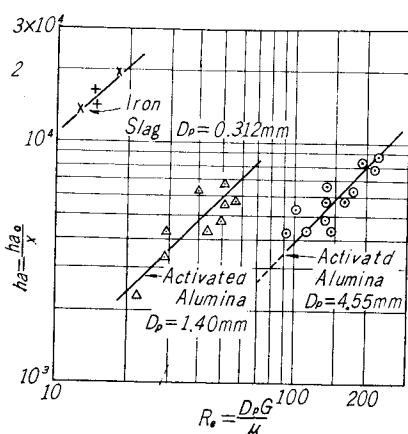


Fig. 5. Correlation of heat transfer coefficient.

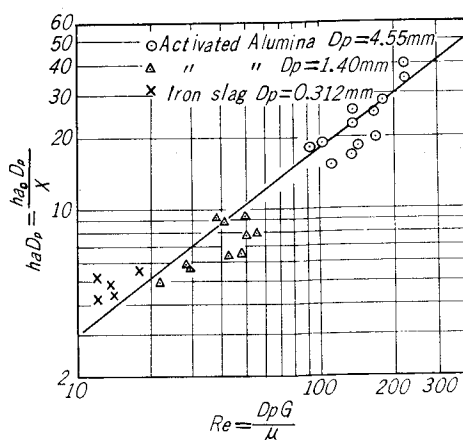


Fig. 6. Correlation of heat transfer coefficients.

$$haD_p = \frac{ha_0 D_p}{X} = 0.476 Re^{0.8} \quad (10)$$

5. Discussion

Heat and mass transfer between fluid and particles in the packed bed were correlated by the excellent work of Hougen and coworkers^{3), 10)}. By the study of the authors⁴⁾, the heat transfer coefficients between fluid and particles in the packed bed were correlated as the equation $Nu = 2.0 + 0.46 Re^{0.75}$. The effective contact area in the unit volume is estimated by $a = \frac{6(1-\epsilon)}{D_p}$, where ϵ is the porosity of packed bed and particles are spherical. Therefore, in order to compare with the heat transfer of the packed bed, the heat transfer coefficients $ha_{calc} = \frac{k}{D_p} (2.0 + 0.40 Re^{0.75}) \frac{6(1-\epsilon)}{D_p}$ were calculated as $\epsilon = 0.4$ and $\frac{ha_{obs}}{ha_{calc}}$ were plotted against D_p as

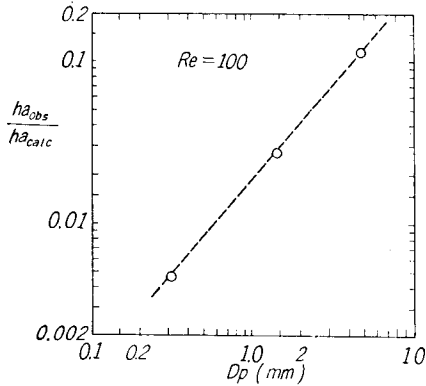


Fig. 7. Comparison between calculated and observed value of heat transfer capacity coefficients.

shown in Fig. 7. From Fig. 7, it is suggested that the effective contact area rapidly decreases with the decreasing of the particle diameter. This result has no generality, however, further work on the effective contact area between fluid and particles would be expected.

6. Conclusion

The heat transfer capacity coefficients of a through flow dryer are correlated as shown in Fig. 6. The heat transfer capacity coefficient ha_0 correspond to the overall heat transfer coefficients Ua which are usually used to design the rotary dryer. In this experiments, the hold up of materials X are from 0.1 to 0.18 and ha_0 are from 500 to 1800 which are larger than that generally obtained by a rotary dryer.

Acknowledgment

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Nomenclature

A	: Area of inside cylinder from which hot air is blown through the bed of material.	(m ²)
a	: Effective area of heat transfer per unit volume of bed.	(m ² /m ³)
C_H	: Humid heat of air	(kcal/kg °C)
C_s	: Specific heat of bone dried material	(kcal/kg °C)
D_p	: Particle diameter	(m)
G	: Mass velocity of air	(kg/hr m ²)
G_0	: Flow rate of dried air	(kg/hr)
F_0	: Feed rate of dried material	(kg/hr)
H_f	: Height of weir at discharge end of material	(m)
h	: Heat transfer coefficient	(kcal/hr m ² °C)
ha	: Heat transfer capacity coefficient	(kcal/hr m ³ °C)
Nu	: Nusselt number	
q	: Heat transferred from hot air to material	(kcal/hr)
r	: Latent heat of evaporation	(kcal/kg)
t	: Air Temperature	(°C)
Suffix 1, 2 indicate the inlet and outlet of bed.		
$(\Delta t)_{lm}$	: Logarithmic mean temperature between gas and material temperature.	(°C)
w	: Water content of material	(kg/kg)
X	: Hold up of material	(fraction)
X'	: Hold up of material	(kg)
τ	: Retention time	

Suffix I and II indicate the preheating zone and constant drying zone.