

HEAT AND MASS TRANSFER BETWEEN GAS AND SOLID PARTICLES IN TRANSVERSE BED OF AERATED ROTARY KILN INCINERATOR

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Gas-solid contact efficiency of a transversely aerated rotary kiln incinerator has proven to be very high. The paper addresses an experimental method to obtain heat and mass transfer coefficients between gas and solid particles in the transverse bed of an aerated rotary kiln incinerator. It is found that the transfer coefficients are sensitive to aeration rate but not to rotation speed. Equations, which correlate the transfer coefficients and relative parameters, are proposed in terms of dimensionless groups to estimate the heat and mass transfer rate in the transverse bed of an aerated rotary kiln incinerator. Furthermore, the temperature distribution in the transverse bed of such a rotary kiln is considered reasonably uniform, which is caused by well distributed inlet gas and solid mixing due to rotation.

Introduction

Gas-solid contact systems have been applied to many industrial processes, such as powder drying, catalytic reaction and solid waste incineration. Rotary kiln is one kind of gas-solid contact systems, and has a long experience in drying and cement industries. Recently, more rotary kiln incinerators are being used for the destruction of hazardous wastes, because it can handle not only solid waste but also sludge very well¹².

Some investigations have been carried out, on the motion and mixing of solid particles in the transverse plane of a conventional rotary kiln. For example, Sawahata¹¹ carried out a series of studies on the circulation rate and mixing time of solid particles. Inoue *et al.*⁵) described a probabilistic approach for the solid mixing in rotary kiln. As for heat transfer, Wes *et al.*¹³) used one-dimensional penetration to analyze the heat transfer between rotary kiln wall and bulk bed. Ito *et al.*⁶) presented an empirical equation for estimating an overall heat transfer coefficient from bed wall to particle bed in rotary drum. McCormik¹⁰) studied the heat transfer between gas and solid particle in a parallel flow rotary kiln. However, the transfer phenomena between gas and solid particles take place only at the axial surface of particle bed, and thus, gas-solid contact efficiency, or combustion intensity for incineration, would not be expected too high in such the rotary kiln.

In fact, contact efficiency and good mixing between gas and solid particles in a rotary kiln are two essential requirements. One of the advantages of transverse aeration in the rotary kiln is the increase of contact surface area between gas and solid particle. As a consequence, it leads to an increase of gas-solid contact efficiency. The high gas-solid contact efficiency would promote the incineration performance of rotary kiln incinerator, such as low CO

emission. Chen and Chang³) used residence time distribution of gas to study the flow model of transverse gas in an aerated rotary kiln. As a proposed concept diagram shown in **Fig. 1**, they found that the gas-solid contact efficiency in an aerated rotary kiln was higher than that in the rotary kiln with parallel flow or counter flow. The rotary kiln system with the concept of transverse aeration has been applied to a commercial incineration system to incinerate 510 tons solid waste per day⁸). The heart of the system is the Westinghouse/O'Connor kiln, a water-cooled rotary barrel constructed of alternating longitudinal water tubes and flat perforated steel plates, which are welded together to form the perimeter. Few reports have been published on the study of the transfer phenomena in the transverse bed of the aerated rotary kiln, which could be a promising incineration system for the reasons described above.

The method, using the characteristics of wet particles in constant-rate drying period, was demonstrated successfully to investigate the heat or mass transfer rate between gas and solid particles²). A drying system can be reasonably considered to be at steady state during constant-rate drying. One of the characteristics during constant-rate drying period is that the water content on a wet particle surface would be approximately equal to the saturated humidity at the particle surface temperature⁴).

Therefore, to obtain the heat and mass transfer coefficients between gas and solid particles in the transverse bed of an aerated rotary kiln incinerator, the paper addresses an experimental method to study the heat and mass transfer by utilizing the characteristics during the constant-rate drying period of wet rice particles. Temperature distribution in the transverse bed of such an aerated rotary kiln incinerator was also measured and discussed.

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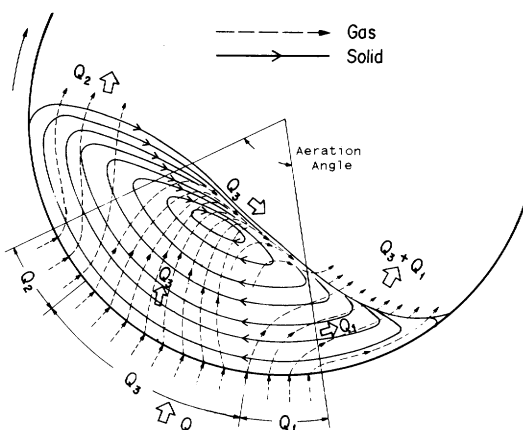


Fig. 1 A concept diagram of transverse flow model in transversely aerated rotary kiln, $Q = Q_1 + Q_2 + Q_3$ ⁽³⁾

1. Background of Theory

At steady state, the energy balance of particle bed in an aerated rotary drum at that the heat transfer rate between gas and solid particles (*e.g.* rice particles) is equal to the latent heat change rate due to humidity change between outlet gas and inlet gas through the bed. Assuming (1) adiabatic rotary drum (energy balance to be checked), and (2) the temperature of solid particle is constant during constant-rate drying period, then:

$$h_c \cdot Ac \cdot Vb \cdot (T_{gi} - T_{go}) / \ln [(T_{gi} - T_s) / (T_{go} - T_s)] = Q \cdot \alpha_w \cdot \rho_g \cdot (H_o - H_i) \quad (1)$$

where logarithmic mean temperature difference is used as driving force, and specific contact surface area, $Ac = 6 (1 - Em) / \phi_s \cdot dp_e$. Thereby, the overall heat transfer coefficient between gas and solid particles is calculated as Eq. (2):

$$h_c = Q \cdot \alpha_w \cdot \rho_g \cdot (H_o - H_i) \cdot \ln [(T_{gi} - T_s) / (T_{go} - T_s)] / Ac \cdot Vb \cdot (T_{gi} - T_{go}) \quad (2)$$

The mechanism of mass transfer between gas and solid particle is that mass (*e.g.* water molecular) transfers from the surface of particle to gas flow. Therefore, the mass transfer rate between gas and solid particles is equal to the humidity change between inlet gas and outlet gas through the aerated rotary drum. A mass balance through the bed is as Eq. (3) with logarithmic mean concentration difference as driving force:

$$k_c \cdot Ac \cdot Vb \cdot \rho_g \cdot (H_o - H_i) / \ln [(H_o - H_s) / (H_i - H_s)] = Q \cdot \rho_g \cdot (H_o - H_i) \quad (3)$$

where H_s is the saturated humidity at particle surface temperature. Because of the characteristic of constant-rate drying mentioned above, the moisture content at solid particle surface is reasonably assumed as H_s during constant-rate drying. Then, the mass transfer coefficient is calculated by the following equation:

$$k_c = Q \cdot \ln [(H_o - H_s) / (H_i - H_s)] / Vb \cdot Ac \quad (4)$$

where H_s is a function of T_s , and can be obtained if T_s is known.

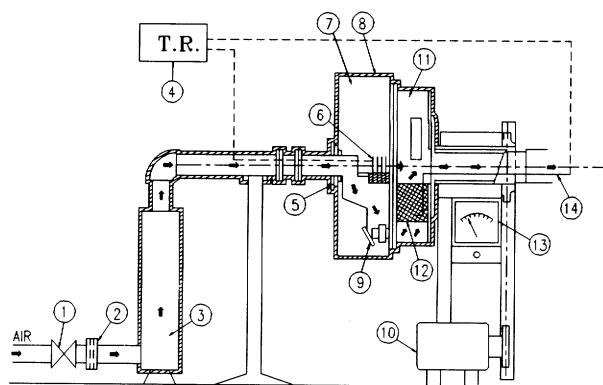


Fig. 2 A schematic diagram of experimental system
1. glove valve 2. flowmeter 3. air heater 4. temperature recorder 5. grand seal 6. mercury contact cell 7. plenum 8. insulating fiber 9. aeration valve 10. geared motor 11. rotary drum 12. particle bed 13. rotation speed controller & indicator 14. thermocouple wires

2. Experiment

A schematic diagram of the experimental system used in the work is shown in **Fig. 2**. The system consists mainly of a 0.3 m diameter and 0.1 m length horizontal rotating drum, made of thermal-resistant resin and installed in a metal shell. The drum was driven and controlled by a variable speed geared motor, and its rotation speed was indicated by a speed indicator. Aerating gas was heated up to 200°C by an electrical heater. In order to adjust the temperature of inlet gas electrical transformer was used to change the output power of the heater. As shown in **Fig. 2**, the hot gas was sent into bed via a stationary pipe and aeration valves. Aeration gas from the valves then passed through the path between two louvre plates, and into particle bed. The valves, rotating with the drum, were controlled to stay open when they passed the fixed inlet aeration position as shown in **Fig. 3**. Gland sealing was used in order to avoid aeration leakage between the stationary gas pipe and rotating part. The system was thermally insulated by glass fiber.

Figure 3 shows a detailed layout of the iron-constantan thermocouples used. The temperatures were recorded by digital instrument, YEW-3874 (Japan). The inlet and outlet humidities were measured by the Novasina MIK-3000 (Swiss) hygrometer which is an electronic instrument (± 1 % accuracy) with capacitive measuring cell and digital display. Humidity reproducibility was also confirmed during the experiments. Because of the measured points of bed wall and inlet gas being rotated with drum, a sliding mercury contact apparatus, as shown in **Fig. 4**, was designed for the electrical connection between the moving and stationary parts of thermocouple wire. The temperature fluctuations, due to rotation, were recorded continuously by the pen recorder of YEW-3056 (Japan). Before a series of experimental runs, zero point of all thermocouples was checked.

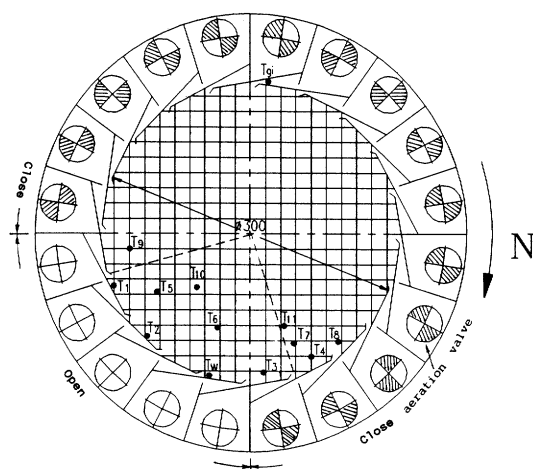


Fig. 3 Detail layout of thermocouples in transverse plane of aerated rotary kiln

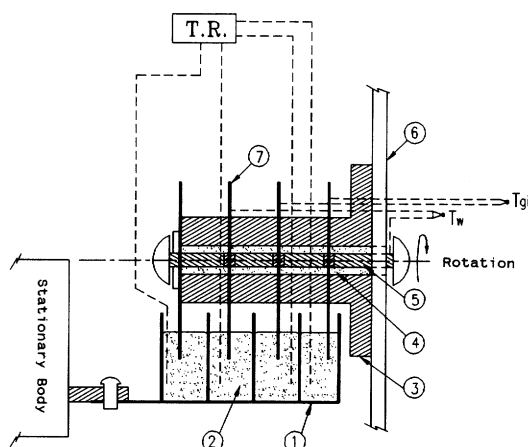


Fig. 4 A schematic diagram of sliding mercury contact cell
1. mercury tub 2. mercury 3. insulating material
4. teflon cylinder 5. copper rod 6. wall of rotary kiln
7. stainless steel disc

Experimental runs to measure synchronously heat and mass transfer were carried out by drying wet rice particles. The wet rice particles had been soaked for over three hours to a 40 % moisture content, before being placed in the rotary drum. The temperatures of solid particles were measured by bare thermocouples (layout as shown in Fig. 3) at packed bed state when the rotation and aeration were abruptly stopped about 5 seconds during experimental running⁸. Both temperatures and humidities were recorded continuously during experimental running. The temperature distributions in the transverse bed of an aerated rotary kiln were also investigated by heating the particle beds of glass bead, SiC particle and marble particle respectively. As shown in Fig. 3, eleven temperatures distributed in the aerated rotary drum were measured during the heating process.

For these experimental runs, the filling volume ratio of solid particles in the drum was about 0.3, aeration rate was in the range of 0.002-0.01 m³/s, which must not be too high to prevent bubbles, and rotation speed was up to 10 rpm. The inlet angle of aeration was 90 degree. **Table**

Table 1. Properties of solid particles used

| solid particle | size [μm] | sphericity [-] | particle density [10 ⁻³ kg/m ³] | repose angle [degree] | voidage in packed bed [-] |
|----------------|-----------|----------------|--|-----------------------|---------------------------|
| Rice | 3310 | 0.76 | 1.361 | 36 | 0.438 |
| Glass Bead | 2735 | 1.00 | 2.501 | 19 | 0.402 |
| Marble | 1971 | 0.63 | 2.611 | 38 | 0.483 |
| SiC Particle | 1054 | 0.60 | 3.280 | 41 | 0.423 |

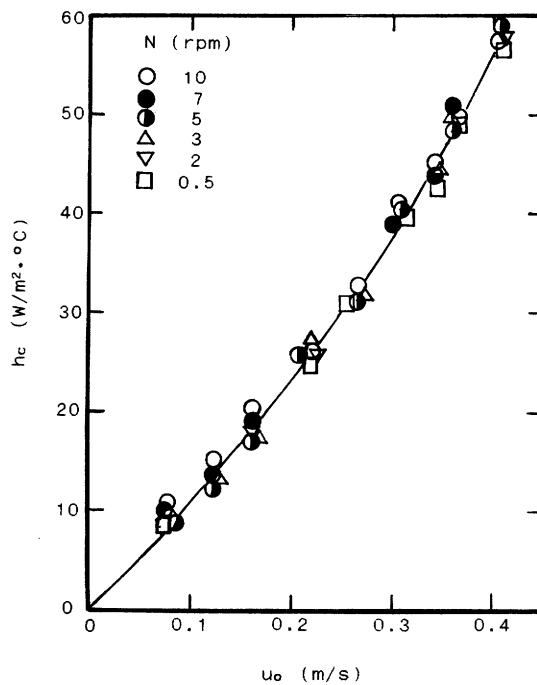


Fig. 5 Relationship between heat transfer coefficient and superficial gas velocity for various rotation speeds

1 presents the properties of the solid particles used.

3. Results and Discussion

A series of experiments to study the heat and mass transfer in aerated rotary drum have been carried out. The experimental results with discussion are described below

3.1 Heat transfer coefficient

Using Eq. (2) with measured experimental data, the heat transfer coefficient, h_c , was calculated. As shown in **Fig. 5**, the experimental result indicates that the heat transfer coefficient is sensitive to aeration rate or superficial gas velocity but not to rotation speed. The relationship between h_c and operation variable, i.e. superficial gas velocity, can be correlated by least square method as $h_c = 211.5 \cdot u_o^{1.358}$, where the superficial gas velocity, u_o , is based on the mean area of inlet gas and outlet gas through particle bed, and the h_c represents an overall heat transfer coefficient. The confidence level of the correlation by least square method is in the range of 0.992 to 0.999 for various rotation speeds. The relationship can also be expressed in terms of dimensionless groups in the following form:

$$Nu_p = 0.019 \cdot Re_p^{1.358} \quad (5)$$

The correlation equation is valid for the Reynolds

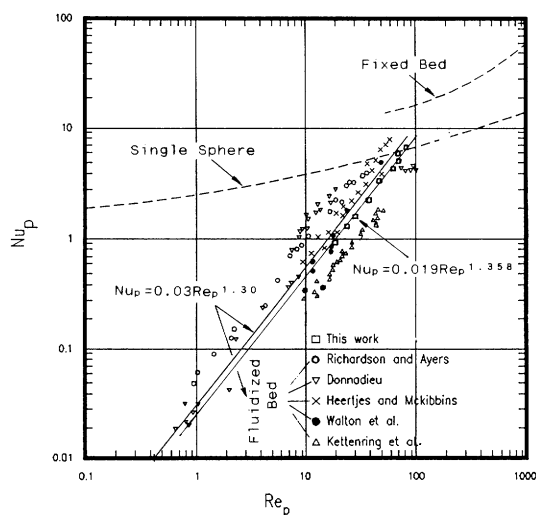


Fig. 6 Comparison on Nu_p among fixed bed, fluidized bed, and aerated rotary kiln^{4,7)}

numbers in the range of 10 to 100, those that are relative to the experimental operation range in this work.

Aerated rotary kiln is one kind of gas-solid contact systems, which include well-known fixed bed, fluidized bed. Therefore, it is interesting to compare the difference of heat transfer coefficients among these gas-solid contact systems. **Figure 6** illustrates the comparison on Nusselt number among fixed bed, fluidized bed and aerated rotary kiln. It is apparent that the relation between Nu_p and Re_p for aerated rotary kiln is similar to that for fluidized bed. It is not easy to give a theoretically sound explanation for why the heat transfer coefficients would be similar between aerated rotary kiln and fluidized bed, because it is difficult to describe accurately gas maldistribution or evaluating the relative velocity of gas passing through solid particle. However, it seems that the effect of gas-solid phenomena on the overall heat transfer is similar either in an aerated rotary kiln or in a fluidized bed.

3.2 Mass transfer coefficient

According to Eq. (4) with measured experimental data, Hi , Ho and T_s (by which H_s is hence obtained), the overall mass transfer coefficients between gas and rice particles were calculated. The results indicate that the mass transfer coefficient increases with the increase of superficial gas velocity as shown in **Fig. 7**. By least square method, the mass transfer coefficient is correlated as a function of superficial gas velocity, u_o , i.e. $k_c = 0.152 \cdot u_o^{1.372}$. The confidence level of the correlation by least square method is in the range of 0.994 to 0.998 for various rotation speeds. In terms of dimensionless groups, it is also expressed as Eq. (6):

$$Sh = 0.0122 \cdot Re_p^{1.372} \quad (6)$$

As same as Eq. (5), the correlation equation is valid for the Reynolds numbers in the range of 10 to 100. **Figure 8** illustrates the comparison on Sherwood number among the aerated rotary kiln, fixed bed and fluidized bed.

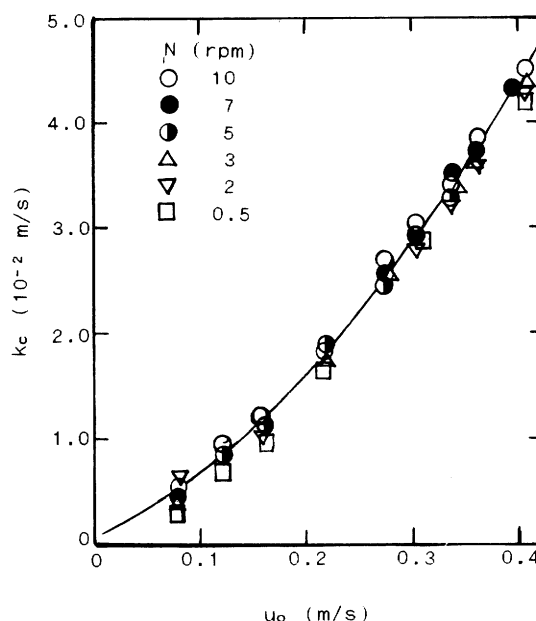


Fig. 7 Relationship between mass transfer coefficient and superficial gas velocity for various rotation speeds

3.3 Effect of rotation on transfer rate

Chen & Chang³⁾ have investigated the effect of rotation on the residence time distribution of gas in an aerated rotary kiln. They found out the significant effect of rotation on the flow pattern of gas in such gas-solid contact system. However, as the experimental results shown in **Fig. 9**, the overall heat and mass transfer coefficients are not influenced significantly by the rotation speed (approaching to zero-order exponential relationship). It may be that the effect derived by gas maldistribution on overall transfer rate is not obvious from the point of view of transfer phenomena, although rotation substantially affects the complex maldistribution of gas flow through the transverse bed of an aerated rotary kiln.

3.4 Bed temperature distribution

The measurements of temperature distribution in the transverse bed were carried out in particle beds of marble, glass bead, and SiC respectively within the aerated rotary drum. The variance of bed temperatures among eleven measured points as shown in Fig. 3 were less than 1.5°C^2 , and the variance decreases slightly as the rotation speed increase of. The transverse bed temperature distribution in the system is considered reasonably uniform. Good transverse mixing in rotary drum was also substantiated by Lehmborg *et al.*¹⁰⁾. Because of well distributed inlet gas in an aerated rotary kiln, it is noted that the bed temperatures at the same radial distance from the drum wall are almost the same, e.g. T_5 , T_6 and T_{11} as shown in Fig. 3. The result appears to be inconsistent with that of nonaerated rotary kiln⁵⁾. Furthermore, the temperature uniformity in the transverse bed of an aerated rotary kiln, due mostly to solid mixing, can be controlled independently by rotation, which distinguishes it from other gas-solid contact systems, like fluidized bed.

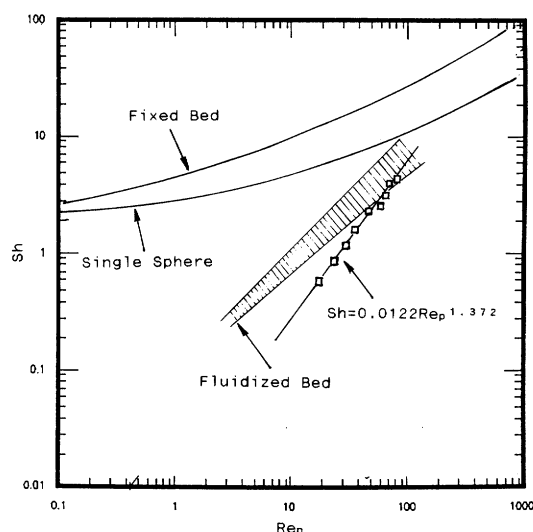


Fig. 8 Comparison on Sh among fixed bed, fluidized bed, and aerated rotary kiln^{1,7)}

3.5 Discussion

The surface temperature of solid particle was directly measured by bare thermocouple at packed bed state during constant-rate drying. It was found that the standard deviations among eleven measured surface temperatures of solid particles were smaller than 1.0°C . During constant-rate drying period, the mean surface temperature of solid particle was also found to maintain a constant level. Those ensure the assumption of T_s as a constant.

An error of energy balance was calculated to make sure of the assumption of adiabatic rotary drum. The experimental results show that the aerated drum used in the work can be considered as an adiabatic system because of the mean value of these errors was less than 3 %. But, it seems that a higher temperature of inlet gas would give a larger error. On the other hand, the heat transfer rate from bed wall to particle bed was also used to check heat loss for the assumption of adiabatic rotary drum. The two equations, proposed by Lehmbert *et al.*⁹⁾ and Ito *et al.*⁶⁾ respectively, were used to calculate the heat enhancement from the drum wall with higher temperature to particle bed in this work. It appears that enhancement is not more than 2 % of the heat transfer rate between gas and solid particles during constant-rate drying period. It results that the heat transfer between bed wall and particle bed is neglected.

Conclusion

The experiments to study the heat and mass transfer in the transverse bed of an aerated rotary kiln have been carried out successfully. The experimental results indicate that both heat and mass transfer coefficients are sensitive to aeration rate but not to rotation speed. Equations, which correlate the transfer coefficients and relative parameters, are proposed in terms of dimensionless groups to estimate the heat and mass transfer rates in the transverse bed of an aerated rotary kiln incinerator. Although the present work applies only to rice particle, it gives a preliminary and prac-

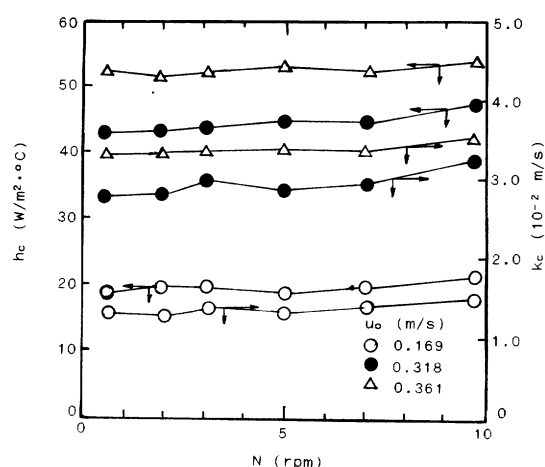


Fig. 9 Effect of rotation speed on h_c and k_c respectively

tical relationship between transfer coefficients and relative parameters.

Temperature distribution in the transverse bed of an aerated rotary kiln is considered reasonably uniform, which is caused by well distributed inlet gas and solid mixing due to rotation. The temperature uniformity in the transverse bed of such an aerated rotary kiln can be controlled independently by rotation.

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Nomenclature

| | | |
|------------|--|---|
| Ac | = contact surface area between gas and solid particles per unit volume of particle bed | $[\text{m}^2/\text{m}^3]$ |
| Cp_g | = specific heat of gas | $[\text{J}/\text{kg}\cdot^{\circ}\text{C}]$ |
| D_{AB} | = diffusivity (moisture in air) | $[\text{m}^2/\text{s}]$ |
| dp_e | = mean particle diameter | $[\text{m}]$ |
| Em | = bed voidage | $[-]$ |
| H | = humidity subscript i for inlet gas, o for outlet gas, and s for saturation | $[\text{kg}\cdot\text{H}_2\text{O}/\text{kg}\cdot\text{Air}]$ |
| h_c | = heat transfer coefficient | $[\text{W}/\text{m}^2\cdot^{\circ}\text{C}]$ |
| k_c | = mass transfer coefficient | $[\text{m}/\text{s}]$ |
| k_g | = heat conductivity of gas | $[\text{W}/\text{m}\cdot^{\circ}\text{C}]$ |
| \dot{N} | = rotation speed of drum | $[\text{rpm}]$ |
| Nu_p | = Nusselt number ($= h_c \cdot dp_e / k_g$) | $[-]$ |
| Q | = total aeration rate | $[\text{m}^3/\text{s}]$ |
| Re_p | = Reynolds number ($= u_o \cdot dp_e \cdot \rho_g / \mu_g$) | $[-]$ |
| Sh | = Sherwood number ($= k_c \cdot dp_e / D_{AB}$) | $[-]$ |
| T_g | = gas temperature, subscript i for inlet, o for outlet | $^{\circ}\text{C}$ |
| T_s | = surface temperature of solid particle | $^{\circ}\text{C}$ |
| u_o | = superficial gas velocity | $[\text{m}/\text{s}]$ |
| Vb | = bulk volume of particle bed | $[\text{m}^3]$ |
| α_w | = latent heat of moisture | $[\text{J}/\text{kg}]$ |
| μ_g | = gas viscosity | $[\text{kg}/\text{m}\cdot\text{s}]$ |
| ρ_g | = gas density | $[\text{kg}/\text{m}^3]$ |
| ϕ_s | = sphericity of solid particle | $[-]$ |

Literature Cited

- 1) Bennett, C.O. and J.E. Myers, "Momentum, Heat and Mass Transfer," 2nd. edn., McGraw-Hill Book Co., New York (1974)
- 2) Bradshaw, R.D. and J.E. Myers: *AIChE J.*, **9** (5), 590 (1963)
- 3) Chen, C.C. and Y.M. Chang: *J. Chem. Eng. Japan*, **22**, 327 (1989)
- 4) DeAcetis, J. and G. Thodos: *Ind. Eng. Chem.*, **52** (12), 1003 (1960)

- 5) Inoue, I.; K. Yamaguchi, and K. Sato: *Kagaku Kogaku*, **3** (12), 1323 (1970)
- 6) Ito, N.; K. Obata, and T. Hakuta: *Kagaku Kogaku Ronbunshu*, **9** (6), 628 (1983)
- 7) Kunii, D. and O. Levenspiel, "Fluidization Engineering," Ch.8, Wiley Press, New York (1969)
- 8) Lee, C.C. and G.L. Huffman, "Update of Innovative Thermal Detraction Technology," US Environmental Protection Agency, Cincinnati, OH, Report No. EPA/600/D-88/225 (1988)
- 9) Lehmberg, J.; M. Hehl and K. Schugerl, *Powder Technology*, **18** (2), 149 (1977)
- 10) McCormik, P.Y.: *Chem. Eng. Prog.*, **58** (6), 57 (1962)
- 11) Sawahata, Y., J. of the Society of Material Science, Japan, No.164, 364 (1967)
- 12) Theodore, L. and J. Reynolds, "Introduction to Hazardous Waste Incineration," Ch.7, John Wiley and Sons, New York (1987)
- 13) Wes, G.W.J.; A.A.H. Drinkenburg, and S. Stemerding: *Powder Technology*, **13** (2), 185 (1976)