Computer Simulation of a Rotary Dryer

Part I: Retention Time

A computer model of a single-pass, rotary-drum dryer with or without a center-fill flighting section, describes the drying behavior of wood particles within the drum. This part of a two-part study examines retention time; the second part incorporates heat and mass transfer for the complete drying model. Simulation results with retention time data from a large-scale rotary dryer showed a favorable comparison, with a root mean square error of 14.2%.

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SCOPE

Rotary dryers can process a variety of materials, including wood particles, bark, grain, coal, fertilizer, sand, and other aggregates. For these numerous applications, a wide assortment of dryer configurations has evolved. The drum may consist of a single- or multiple-pass arrangement, operate under cocurrent or countercurrent flow, be fired directly or indirectly, and have various interior lifting-flight configurations. In any case, the principle of operation is the same. The wet particles enter the rotating drum and are then continuously cascaded through the moving gas stream. Particles caught on lifting flights rotate with the drum. With cocurrent flow, a particle falling from a flight is moved along the length of the drum as a result of a drag force imparted by the gas stream. With countercurrent flow, kiln action and a sloped drum work against the gas flow to move the particles through the dryer. Drying occurs primarily by convective heat and mass transfer.

Rotary dryer performance is heavily influenced by the rate of heat transfer from gas to particles and by the retention time of particles in the drum. The drying characteristics of the solids often dictate the required retention time in the drum; therefore, an analysis of heat transfer and factors affecting retention time is important for designing rotary dryers.

In the forest products industry, rotary dryers have been used almost exclusively for drying wood particles in the particleboard manufacturing process. Over the past few years, however, these dryers have increasingly been put to use in conjunction with exhaust stack gases and wood-fired boilers for drying hogged-wood residue. In such applications the operation and design of rotary dryers has largely been an art.

With the coming of computer process control, microprocessors, and improvements in metering and sensing devices, there is opportunity for improving rotary dryer control strategies, providing that the desired product and raw material characteristics can be linked with the necessary operating conditions.

This paper comprises the first part of a two-part study directed toward developing a computer model of the drying behavior of wood particles in a rotary dryer. It analyzes those factors affecting the retention time of particles within a rotary drum, providing information on particle location and behavior with the gas stream. Part II reports on simultaneous heat and mass transfer for a complete drying analysis. The model is based on first principles and empirical correlations, which were derived independently of rotary dryers. In addition, we conducted a series of experiments measuring retention time and drying characteristics in a large-scale rotary dryer, and compared the results to predictions from the computer model. Retention time measurements were made by means of a radioactive tracer technique.

CONCLUSIONS AND SIGNIFICANCE

Comparison of measured retention time with the results from the computer simulation yielded a root mean square error of 14.2%, averaged over all test runs. The simulation results compared most favorably when the characteristic particle dimension was represented by the mean size of all particles rather than discrete size of individual particles.

The simulation predicted a much larger effect of individual particle size than was measured experimentally, a discrepancy due to the assumption that the particles behave independently in the gas stream. Measured retention times of individual particles ranging in screen size from 1.53 to 5.14 mm showed no significant difference, indicating that cascading particles do not behave independently but are influenced by bulk particle flow. Within the size range examined, interaction between particles completely masked effects of individual particle size.

Computer simulations predicted that retention time decreases nonlinearly with an increase in gas velocity, while at higher velocities this effect diminishes. Retention time decreases nonlinearly with increasing drum speed. Increasing the drum diameter caused a nearly proportional decline in the retention time. Results of the retention time simulation may be used directly for modeling heat and mass transfer characteristics in a rotary dryer.

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BACKGROUND

Retention time in rotary dryers is dependent on the particle flow path, which consists of flow in a gas-particle stream and travel on lifting flights. The arrangement and shape of the lifting flights influences the flow path. Two possible flighting systems for a single-pass rotary dryer are shown in Figure 1. The broken lines indicate possible paths for a particle along the length of the drum. Other factors that influence retention time are gas flow rate, particle feed rate, particle characteristics, drum diameter, drum length, drum slope, and rate of drum rotation.

Early research on retention time concentrated on developing empirical correlations from experiments with small-scale rotary drums. The work of Friedman and Marshall (1949) and their summary of the work of Prutton et al. (1942) and Smith (1942) on retention time and holdup in rotary drums is the broadest data base available, covering a variety of materials and operating conditions. Friedman and Marshall's correlation for retention time in a single-pass, open-center drum, with cocurrent or countercurrent flow, is the most often cited empirical approach (Perry and Chilton, 1975):

$$t = \frac{13.8\,L}{(\tan\alpha)N^{0.9}D_d} \pm 0.59\,\frac{LG}{SD_p^{0.5}} \tag{1}$$

Saeman and Mitchell (1954) used a graphical analysis of the drum and lifting flight cross section to examine particle trajectories and thus to predict retention time distributions. Miskell and Marshall (1956) studied retention time in a drum of 0.14 m diameter with radioactive tracers. Results showed an optimum holdup condition at which deviation from the average retention time was minimized.

Theoretical retention time models have been developed by Schofield and Glikin (1962), Kelly and O'Donnell (1968, 1977), Glikin (1978), Kisakürek (1982), and Platin et al. (1982). The concept of a cascade cycle was incorporated into all of these models, in which a fluid dynamic analysis of the gas-particle interaction was critical. Glikin's model predicts retention time in a single-pass, open-center drum as follows:

$$t = \frac{L_e}{\bar{y}\left[\sin\alpha \pm \frac{Jv_r^2}{g}\right]}\left[\frac{\bar{\theta}}{3N} + \left(\frac{2\bar{y}}{g}\right)^{0.5}\right] \tag{2}$$

The drag factor, J, and the relative particle velocity, v_r, are calculated with empirical correlations relating particle characteristics to gas velocity, and with the assumption that particles behave independently when they fall through the gas stream. The effective drum length, L_e, is derived through experiment with rotary drums. Kelly and O'Donnell's model is similar, but includes the effects of kiln action and particle bouncing.

Because of the diversity in rotary dryer design, it is difficult for one model to handle all possible dryer configurations and operating conditions. All work reported thus far has dealt only with a single-pass, open-center drum. Experimental work has been limited to small-scale laboratory drums.

This study considers single-pass drums with an allowance for centerfill flights, as shown on the right in Figure 1. A computer program was developed to predict the average retention time at any point along the drum length. The model does not require empirical constants or correlations derived from experiments with rotary dryers. We compared data collected from a large-scale rotary dryer to simulation results from the computer program.

MODEL DEVELOPMENT

Incorporated into the model of rotary drum retention time are these assumptions:

1. Particles fall independently of one another with no particle-to-particle interaction.
2. Irregularly shaped wood particles may be approximated as spheres for purposes of analyzing the gas and particle interaction.
3. The particle lifting flights are rectangular in cross section or may be approximated as such (Figure 2).
4. The drum is single-pass, with or without centerfill flights.

A force balance equation for a spherical particle falling in crossflow to a moving gas stream was presented by Schofield and Glikin (1962) as:

$$\frac{\pi}{6}D_p^3\rho_p\left(\frac{dv_x}{dt}\right) = \frac{\pi}{6}D_p^3\rho_p g\sin\alpha + C_D\rho_G\frac{\pi}{4}D_p^2\frac{(v_G - v_x)^2}{2} \tag{3}$$

From left to right, the terms represent inertial force, force due to gravity, and drag force on a particle, all in the longitudinal direction. This relation may be integrated twice to yield the longitudinal advance of a particle per cascade:

$$x = v_G t_f + \frac{1}{K}\ln\left\{\frac{\cos[\tan^{-1}(v_G/a)]}{\cos[-aKt_f + \tan^{-1}(v_G/a)]}\right\} \tag{4}$$

In analyzing rotary dryers, the drag coefficient, C_D, has been estimated under assumption 1 using Eq. 5 (Glikin, 1978; Kelly and O'Donnell, 1968, 1977; Thorne, 1979), which was originally developed by Schiller and Naumann (1933) for spherical bodies in motion under a gravitational force:

$$F_D = 3\pi D_p v_r \mu(1 + 0.15\,Re^{0.687}) \tag{5}$$

Combining the last term in Eq. 3 with Eq. 5, the drag coefficient may be evaluated as:

$$C_D = \frac{24}{Re}(1 + 0.15\,Re^{0.687}) \tag{6}$$

Since the drag coefficient is a function of the relative particle velocity, Eq. 4 and 6 must be solved iteratively.

In a rotating drum with both outer and centerfill flights, the

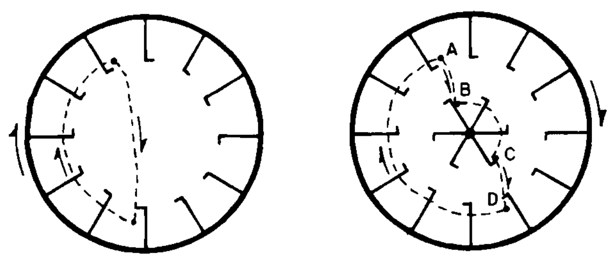

Figure 1. Rotary-drum cross sections showing possible particle cascade patterns in an open-center drum (left) without and (right) with centerfill flights.

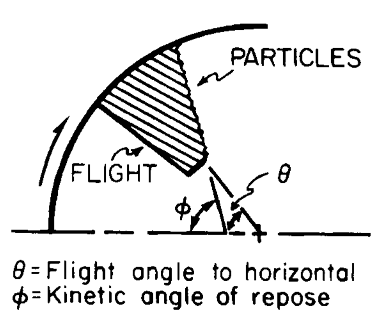

Figure 2. Cross section view of particles in a rectangular flight.

time of travel on lifting flights consists of that on both outer and centerfill flights (between points D and A and points B and C in Figure 1). Likewise, the time of fall through the gas stream consists of fall from both outer and centerfill flights (between points A and B and points C and D in Figure 1). Points A, B, C, and D represent a possible cascade in the travel of a particle. The average positions of these points may be defined by a technique presented by Glikin (1978) for outer flights and modified by Kamke (1984) for centertill flights. For point A, the average outer flight angle from which a particle falls is given as:

$$\bar{\theta} = \frac{1}{h^*(0)} \int_0^{h^*(0)} \theta \, dh^* \tag{7}$$

For point C, the average centerfill flight angle from which a particle falls is given as:

$$\bar{\Psi} = \frac{1}{h_c(\Psi_i)} \int_0^{h_c(\Psi_i)} \Psi \, dh_c \tag{8}$$

To integrate Eqs. 7 and 8, a relationship is needed between the flight angle and the flight holdup. This is derived from a knowledge of the flight geometry and the characteristic kinetic angle of repose of the particles. Glikin (1978) gives this relationship for the outer rectangular flight shown in Figure 2. A similar relationship has been developed for centerfill flights (Kamke, 1984).

The average angle of entry onto the centerfill flights, $\bar{\Psi}_e$, and the average angle of entry onto the outer flights, $\bar{\theta}_e$, are represented by points B and D, respectively, in Figure 1. If a completely vertical fall is assumed, these angles, and the distance of particle fall, y, may be determined by plane geometry.

The time of fall, t_f, is then approximated as:

$$t_f = (2gy)^{0.5} + (2gy_c)^{0.5} \tag{9}$$

and the time of travel on the flights is given by:

$$t = [(360 + \bar{\theta} - \bar{\theta}_e) + (\bar{\Psi} - \bar{\Psi}_e)]/(360\, N) \tag{10}$$

The total retention time is calculated by Eq. 11, in which the number of cascades, C, is determined by dividing the length of the drum by the longitudinal advance per cascade, x, from Eq. 4.

$$t_T = C(t + t_f) \tag{11}$$

The analysis has so far assumed that the drum is fully loaded. This means that at $\theta = 0$ the flight is filled to capacity and cascading begins. Overloading the drum, such that a portion of the holdup bypasses the lifting flights, is undesirable because material accumulating on the bottom of the drum will not participate in continual cascading. Particle feed rates are often limited by burner capacity and drying rates. Therefore overloading is not likely to occur under normal operating conditions.

For underloading of the drum, which is the most likely case, cascading begins at some peripheral flight angle greater than zero; therefore Eq. 7 must be modified. An iterative procedure is proposed. First, retention time and holdup are calculated as we have outlined. The calculated drum holdup is then compared to the known design holdup for the drum and the material being processed. A fractional drum holdup is determined as $m = H/H^*$. If the fractional drum holdup is less than one, an iteration is required. If drum holdup is assumed to be proportional to flight holdup, a new value for the flight holdup when cascading begins may be calculated as:

$$h(\theta_i) = mh^*(0) \tag{12}$$

This value is then compared to successive values of $h^*(\theta)$ as θ is increased until $h(\theta_i)$ just exceeds $h^*(\theta)$, at which point the peripheral flight angle when cascading begins will be identified. Equation 7 then becomes:

$$\bar{\theta} = \frac{1}{h(\theta_i)} \int_0^{h(\theta_i)} \theta \, dh \tag{13}$$

The procedure for calculating the total retention time and drum holdup is repeated, and successive iterations are performed until convergence is achieved.

It is common practice to approximate the fluid dynamic properties of irregularly shaped particles to another shape, such as a sphere, and to calculate an equivalent particle diameter (Torobin and Gauvin, 1960; Heywood, 1962; Mason, 1980). A method proposed by Levenspiel (1984), which is based on a sieve screen analysis, is given by:

$$D_p = \sigma \cdot D_s \tag{14}$$

The angle of repose (Figure 2) for particles being carried in lifting flights is simply the angle of the particle bed surface relative to the horizontal. When the particle bed is in motion, this is known as the kinetic angle of repose.

Kamke (1984) used a photographic technique to study the kinetic angle of repose for sawdust, examining the effects of particle moisture content, drum speed, and drum diameter. The kinetic angle of repose was found to be independent of the Froude number within the range of $200 < Fr < 100{,}000$. There was a slight dependence on the angle of the flight relative to the horizontal and a significant dependence on moisture content in the range of $0.10 < X < 1.46$. The mean kinetic angle of repose was approximately 82.6 degrees, which is somewhat higher than the 71 degrees previously reported by Friedman and Marshall (1949) for sawdust of unknown moisture content.

EXPERIMENTAL

A commercially designed and manufactured rotary dryer was used in the experimental portion of this work; the drum is 1.2 m in diameter and 5.5 m in length, with six centerfill and twelve outer flights (Figure 1, right). Wood particles entering the drum through a screw-feed conveyor come in contact with the conveying gas at the entrance in a cocurrent flow (Figure 3). Wood particles and gas exit the drum into a drop-out hopper, at which point approximately 90% of the particles are collected. The remaining fines and exhaust gas travel to the cyclone separation system, where most of the fines are removed. Other minute particulates and the exhaust gas pass through an induction fan and out the stack. For the retention time experiment, the drum was operated at ambient conditions with wood particles that were previously dried.

Retention time was measured by a radioactive tracer technique in which representative test particles were tagged with a radioactive isotope. The signals from two NaI gamma ray detectors inside the drop-out hopper were individually processed through a separate preamplifier and amplifier circuit (Figure 3). The two signals were then joined and routed through a single rate meter, and the output was transmitted to a strip-chart recorder. A remote switch at the particle inlet manually controlled the strip-chart recorder and initiated the starting time for each run. Air flow was monitored by a venturi in the exhaust gas stream, and the particle feed rate was continuously metered through a conveyor belt balance in front of the inlet screw-feed conveyor.

The wood particles were commercially prepared. Their size distribution, with a calculated mean sphericity of 0.75, is shown in Figure 4. The relative frequency is the weight fraction divided by the incremental screen opening. Representative test particles were selected from three size classes defined by a screen analysis; total dry weight was 1.2 g per size class. Enough particles for six test runs were prepared.

Test particles were tagged with a predetermined amount of an aqueous solution of Na^{24}, a neutron-rich isotope of Na^{23}. This nuclide was selected because of its relatively energetic gamma rays at 1.37 and 2.75 MeV per disintegration and because the test site location and travel time were in keeping with the 15 h half-life.

Before the test runs, the tagged particles and the bulk particles to be fed into the drum were dried to approximate equilibrium in ambient conditions. At the start of each test run, the tagged particles were simultaneously injected through an access port at the particle inlet immedi-

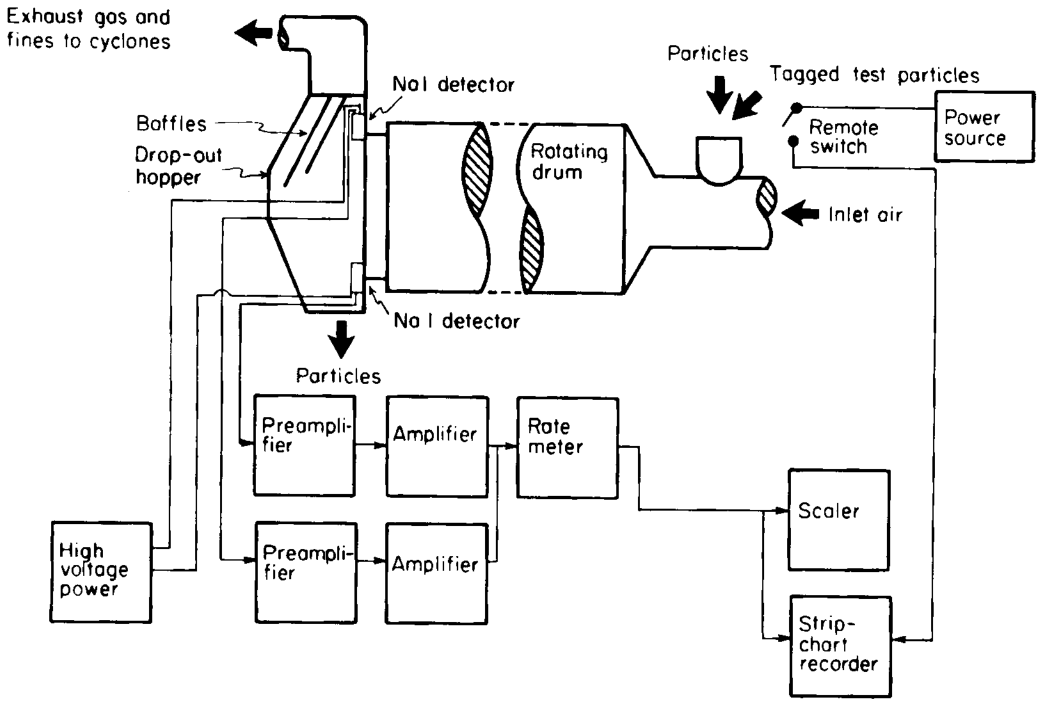

Figure 3. Experimental setup for measuring retention time by means of a radioactive tracer detection system.

ately ahead of the rotating drum. Tagged particles were mixed with the bulk particle feed just before entering the drum.

RESULTS

Frequency histograms were prepared from the output of the strip-chart recorder (Figure 5), and means and standard deviations were plotted with mean retention time predictions from the computer program (Figure 6).

The effect of drum speed is readily apparent in Figure 6. Increasing the speed decreased the average retention time. Of particular interest is the effect of particle size, which the computer model predicted to be more significant than was shown by the data. The model assumes the particles act independently; experimentation showed that this was not the case. Test particles of discrete size were injected into the rotary drum and mixed immediately with the bulk particle flow. During a cascade, the particles fall in curtains, separated by relatively particle-free areas. Within a curtain, particle contact and shielding

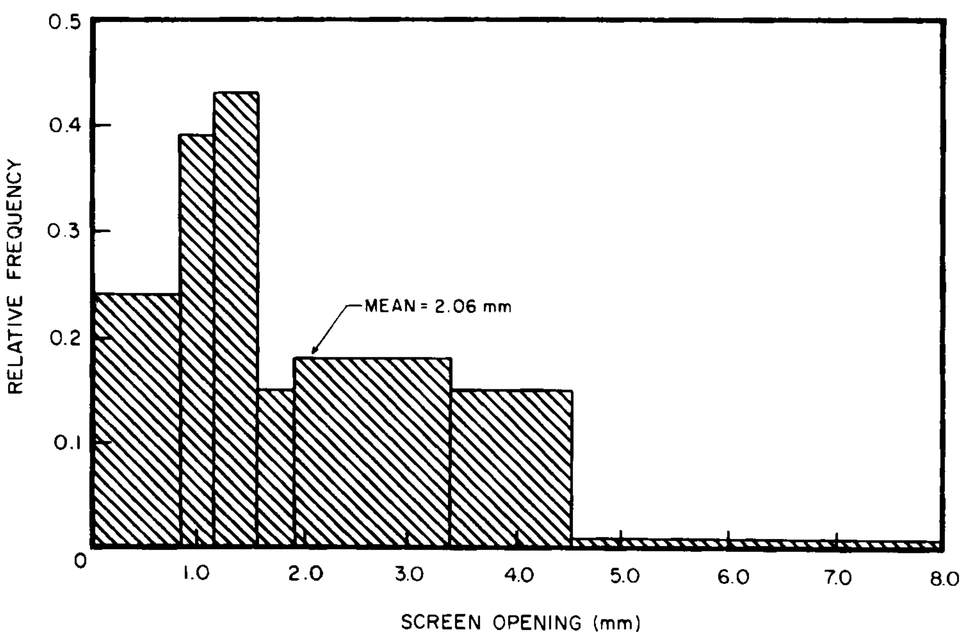

Figure 4. Wood particle size distribution used in retention time study. Relative frequency = weight fraction ÷ incremental screen opening (Sweco).

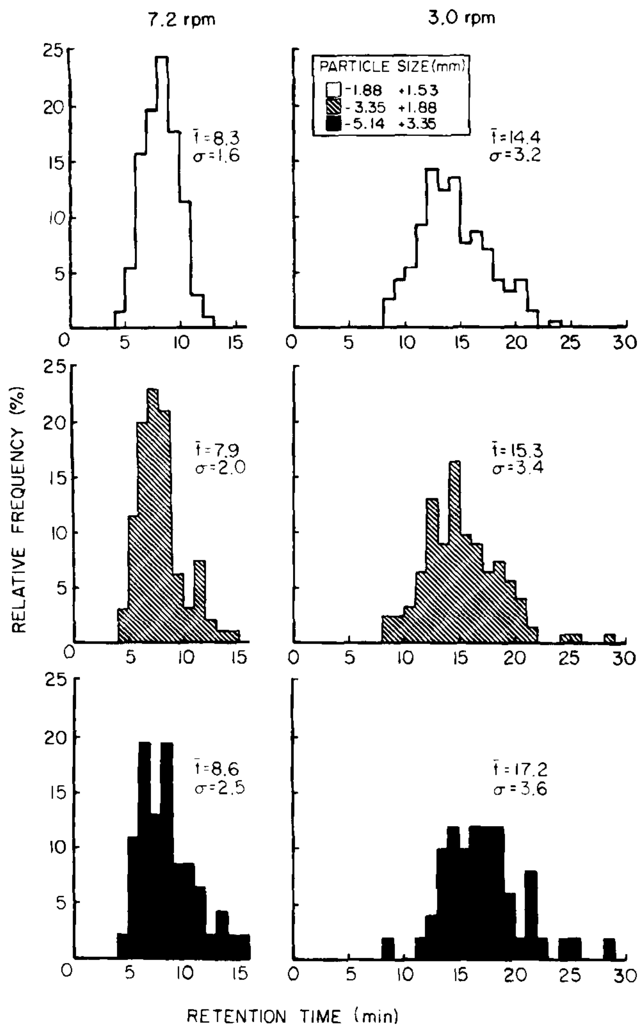

Figure 5. Measured retention time distributions with gas velocity 1.58 m/s and feed rate 0.334 dry kg/s.

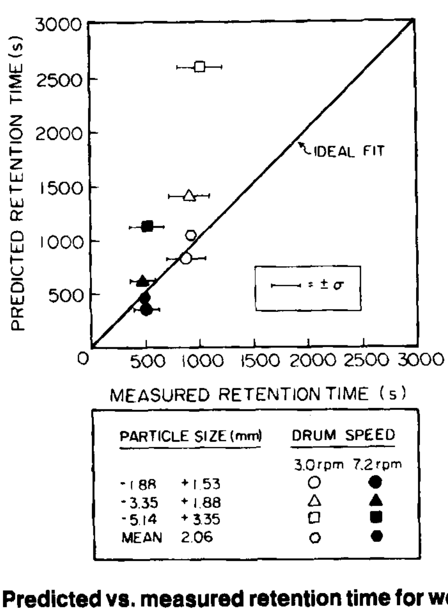

Figure 6. Predicted vs. measured retention time for wood particles in the rotary drum with gas velocity 1.58 m/s and feed rate 0.334 dry kg/s.

of the gas flow by other particles can affect flow. The denser the curtain, the more interaction. As a result, individual particle flow is influenced by bulk particle flow.

If particles behave as a group in gas-particle interaction, a representative particle dimension on which to base a drag coefficient calculation would be mean particle size (Figure 4). We plotted retention time with the mean particle size (Figure 6) against measured retention time averaged over each drum rotation rate. The combined root mean square error for all test runs based on the discrete test particle size was 109.6%; based on the mean particle size, it was 14.2%.

Kelly and O'Donnell (1977) recorded a root mean square error of 23.2% for their predictions of retention time of pumice particles in a drum 0.31 m in diameter with no centerfill. Their retention time data were taken in a test section of the drum that was less than 0.5 m long. Both the test particles and the bulk particles were a discrete size. Kelly and O'Donnell's study incorporated the effects of kiln motion and particle bouncing, both of which result from a sloped drum. The rotary drum of our study was not sloped.

The accuracy of Kelly and O'Donnell's model declined as air velocity increased. At 1.61 m/s the root mean square error was 34.1%. The air velocity in our study was approximately the same at 1.58 m/s; the root mean square error was 14.2%.

We conducted a series of computer simulation trials to examine the effects of various process parameters on retention time. Figure 7 (left) shows a plot of retention time as a function of gas velocity. The three lines represent different drum holdups as a fraction of the design (fully loaded) drum holdup. As expected, retention time decreases with increasing gas velocity; the effect diminishes at the higher gas velocities examined. A plot of retention time as a function of drum rotation rate showed that increasing the speed decreases the retention time (Figure 7, center). The effect appears to be nonlinear over the entire range of drum speeds examined. Increasing the drum diameter decreases the retention time (Figure 7, right) because the longer distance of particle fall with the larger diameters allows a longer time for gas and particle interaction.

In all instances, the fractional drum holdup was inversely related to retention time. Fractional drum holdup was varied by changing the particle feed rate. Holdup, feed rate, and retention time are related as follows:

$$t = \frac{H}{S}\rho_B \tag{15}$$

Changing the particle feed rate resulted in a less than proportional change in the drum holdup, which indicates that retention time is more sensitive to such changes than is drum holdup. This result is confirmed by the data of Saeman and Mitchell (1954) and Kelly and O'Donnell (1977).

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NOTATION

$a = \left[g \frac{\sin \alpha}{K} \right]^{0.5}$

C = number of cascades

C_D = drag coefficient

D = diameter, m

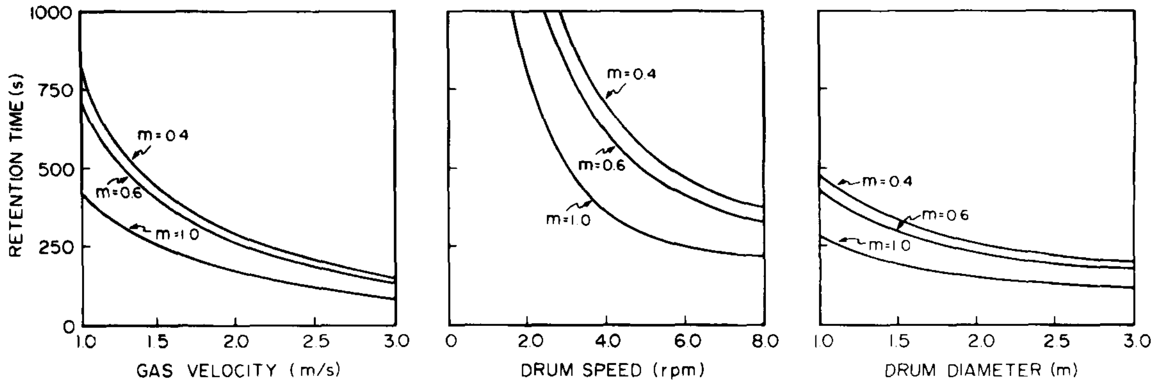

Figure 7. Predicted effect of gas velocity, drum speed, and drum diameter on retention time.

D_s = mean aperture size of two screens defining a particle size, m
F_D = drag force, N
Fr = Froude number
g = acceleration due to gravity, m/s^2
G = dry gas mass flow rate, kg/s
h = flight holdup, m^3
H = drum holdup, m^3
J = drag factor

$$K = 0.75\, C_D \frac{\rho_G}{D_p \rho_p}$$

L = drum length, m
L_e = effective drum length, m
m = ratio of actual holdup to design holdup
N = drum rotation rate, rev/min
Re = Reynolds number
S = dry solids feed rate, kg/s
t = time, s
v = velocity, m/s
$v_r = v_G - v_x$ = relative particle velocity, m/s
x = longitudinal advance of a particle per cascade, m
X = moisture content of the wood, dry basis
y = vertical distance of particle fall, m

Greek Letters

α = drum slope to horizontal, degrees
θ = peripheral flight angle, degrees
θ_e = peripheral flight angle of entry, degrees
θ_i = peripheral flight angle when cascading begins, degrees
μ = viscosity, Pa · s
π = 3.1416
ρ = density, kg/m^3
σ = sphericity
ϕ = kinetic angle of repose, degrees
Ψ = centerfill flight angle, degrees
Ψ_e = centerfill flight angle of entry, degrees
Ψ_i = centerfill flight angle when cascading begins, degrees

Subscripts

B = bulk
c = centerfill flight
d = drum
e = peripheral flight
f = particle fall
G = gas
p = particle or solids
T = total
x = directional coordinate

Superscripts

$*$ = design condition
$\_$ = average

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