Computer Simulation of a Rotary Dryer

Part II: Heat and Mass Transfer

A computer model of a single-pass, rotary-drum dryer with or without a centerfill flighting section, describes the drying behavior of wood particles within the drum. This part of a two-part study examines heat and mass transfer, which are shown to be partly dependent on the pattern of particle flow and on retention time. Comparison of simulation results with drying data based on moisture content of outlet particles from a large-scale rotary dryer was favorable, with a root mean square error of 22.2%.

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SCOPE

The presentation of particles relative to the hot gas stream in a rotary dryer influences the drying rate. The retention time analysis from Part I of this study was used as the basis for the overall rotary drying model for wood particles. Material and energy balance equations and a drying rate relationship are solved simultaneously over incremental dryer lengths. Within each increment, the drying rate is calculated from empirical correlations for convective heat transfer to particles in a gas stream and from the drying rate of wood.

Previous work in this area has included both empirical and theoretical modeling of the rotary drying process, the most recent studies concentrating on developing computer programs for theoretical drying behavior. All have dealt only with single-pass, open-center drums, and no experimental work has been reported on drying of wood particles in rotary dryers.

The primary objective of this study was to develop a computer model of a single-pass rotary dryer with or without centerfill flights. Results of experiments in which wood particles were dried in a large-scale rotary dryer containing centerfill flights are compared to the model predictions.

CONCLUSIONS AND SIGNIFICANCE

Comparison of the measured moisture content of outlet particles in a rotary drying experiment to that of computer predictions resulted in a root mean square error of 22.2% for six test runs. The simulation profiles for particle moisture content, gas temperature, and particle temperature agreed well with their measured counterparts along the entire dryer length.

Simulation of the sensitivity of the predicted outlet particle moisture content to selected parameters yielded a decreasing order of importance: inlet particle moisture content, inlet gas temperature, drum diameter, air leakage, drum length, gas flow rate, particle size, particle sphericity, drum speed, angle of repose, and an empirical wood-drying constant known as the bend factor.

Due to counteracting effects of retention time and the local rate of heat transfer, there is an optimum gas flow rate for maximum drying.

Solid conclusions concerning the validity of the model assumptions cannot be made from the limited amount of data collected on a single drying system; however, over the conditions examined, the model performed well. This rotary dryer model may supplement more time-consuming and expensive experimental methods used for dryer control and design.

BACKGROUND

Upon entering a rotary dryer, hot gas comes in contact with cooler, wet solids. Heat is transferred from the gas to the wet solids as a result of a temperature driving force, and the solids increase in temperature and lose moisture at the expense of sensible and latent heat effects. The resultant water vapor is then transferred to the gas stream under a vapor pressure gradient. This process is characterized by simultaneous momentum, heat, and mass transfer as the solids continue a cyclic cascading pattern throughout the drum cross section from the inlet to the outlet. In this complex process, the heat transfer component is often analyzed in terms of a volumetric heat transfer coefficient, U, as follows:

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$$Q_S = UV_d\,\Delta T_{\ell m} \tag{1}$$

Attempts have been made to correlate U with gas flow rate, rate of drum rotation, drum diameter, and the number of lifting flights. McCormick (1962) surveyed the earlier work of Miller et al. (1942), Friedman and Marshall (1949), and Saeman and Mitchell (1954) to derive the following:

$$U = KL_dD_d(G/A_d)^{0.67} \tag{2}$$

where K is an empirically derived constant. The success of these correlations is limited to specific applications, since most of the data was collected from small, single-pass rotary drums with open centers.

Kuramae and Tanaka (1977) and Hirosue and Shinohara (1978) used a theoretical approach to derive relationships for volumetric heat transfer coefficients, starting with estimates of individual coefficients of surface-film heat transfer. Porter (1963) and Turner (1966) were the first to analyze the cyclic heat-transfer mechanisms occurring during alternate periods of falling and soaking of individual particles. The theoretical approach to heat transfer analysis requires a detailed examination of the cascading pattern, such that the conditions of the gas and particle interaction are well defined.

Within the rotary-drying process, the process of mass transfer cannot be isolated, as the removal of moisture is dependent on the transfer of heat. Myklestad (1963) developed a procedure for predicting the moisture-content profile of solids along the length of a rotary dryer by assuming that gas temperature is linearly related to their moisture content. From drying tests with pumice, he found a variation in the calculated volumetric heat transfer coefficient to the 0.8 power of the gas mass velocity. A more fundamental approach used by Sharples et al. (1964) required the simultaneous solution of four differential equations for energy and material balances. Empirical coefficients were required to estimate the volumetric heat transfer coefficient and the solids drying rate. Davidson et al. (1969), examining the alternating periods of falling and soaking, extended the work of Porter (1963) and Turner (1966) to include mass transfer. Thorne (1979) combined the work of Kelly and O'Donnell (1977) on retention time with the vapor-diffusion model of Garside et al. (1970) to develop a computer simulation model of a single-pass, open-center rotary dryer. Experiments with drying pumice appeared to agree well with the model predictions; however, the retention time calculation was altered to better match retention time measurements before the drying calculations were performed. A simplified rotary-drying model (Kisakürek, 1982) was made by assuming a constant solids temperature and by neglecting sensible heat effects. This model performed poorly at low moisture contents; predictions did not compare well with drying data for gypsum particles. In a computer program in which external convective heat transfer to the solids was assumed to control the drying process (Platin et al., 1982), the solids were taken to be ideally porous, such that internal moisture movement was rapid enough to keep the particle surface wetted throughout the course of drying. No experimental support was provided.

As was apparent with the retention time analysis in Part I of this study, variations in the flighting configuration affect the heat transfer characteristics of the dryer. Dryer performance is also influenced by the particular drying character of the solid. Thus far, the literature has dealt only with single-pass, open-center rotary dryers, and most of the data available are for sand and other aggregates in small-scale laboratory dryers.

MODEL DEVELOPMENT

In addition to the assumptions outlined in our previous study, the following assumptions are also incorporated in the development of the rotary dryer model:

1. Heat and mass transfer to and from particles occurs only during the period of fall.
2. While particles are on a lifting flight, no heat or mass is transferred across the particle surface; however, transfer occurs internally, such that at the end of the soaking period heat and moisture profiles within particles are uniform.
3. Gas temperature is uniform relative to the drum cross section.
4. Wood particles do not change dimensions due to changes in moisture content.

Characteristics of the particle flow path defined in the retention time analysis may be used as a basis for developing the heat and mass transfer relationships. Equations for material and energy balance can be coupled with a drying-rate expression to describe drying progress along the length of a rotary dryer. The drum is divided into segments, each defined as one cascade length (Figure 1). Steady state conditions are assumed within each segment.

Material and energy balance equations for one drum segment are, respectively:

$$G(1 + Y_i) + S(1 + X_i) = G(1 + Y_{i+1}) + S(1 + X_{i+1}) \tag{3}$$

$$G\left[\int_{T_{ref}}^{T_{Gi}} (c_G + Y_ic_v)\,dT_G + Y_i\lambda_{ref}\right] + S\int_{T_{ref}}^{T_{Si}} (c_S + X_ic_w)\,dT_S$$
$$= G\left[\int_{T_{ref}}^{T_{Gi+1}} (c_G + Y_{i+1}c_v)\,dT_G + Y_{i+1}\lambda_{ref}\right]$$
$$+ S\int_{T_{ref}}^{T_{Si+1}} (c_S + X_{i+1}c_w)\,dT_S + Q_L \tag{4}$$

The temperature reference condition, designated by the subscript *ref*, is taken as liquid water at 0°C. Thermal properties of the particles and the gas are assumed to be constant over each drum segment and are evaluated at the mean temperature and moisture content.

Heat loss is defined as the net energy loss from the combined gas and particle stream within each segment. Air leakage occurs before the drum inlet or after the drum outlet; consequently, all heat losses are attributed to combined conduction, forced-convection, free-convection and radiation heat transfer through the drum wall. Heat loss for each segment is estimated as:

$$Q_L = (T_G - T_A)/R_T \tag{5}$$

A calculation of the thermal resistance of the drum wall given by Kamke (1984) is based on empirical correlations of heat transfer from rotating cylinders and on fundamental principles of conduction and radiation heat transfer (Kays and Bjorklund, 1958; Welty, 1974; Welty et al., 1976).

The extent of drying within each drum segment is estimated by means of the empirical wood drying model proposed by Rosen (1982):

$$\frac{X - X_e}{X_o - X_e} = 1 - \dot{E}_o \int_0^t \exp(-at^{1/b})\,dt \tag{6}$$

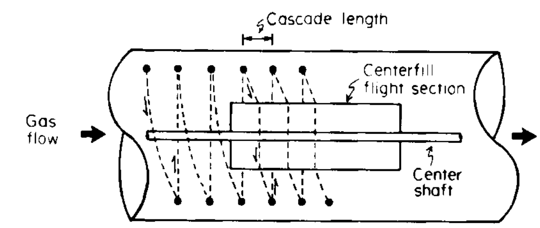

Figure 1. Longitudinal section of a rotary drum with centerfill flights showing the cascade cycles, each defining a control volume for the material and energy balance equations.

The terms a and b are empirical constants—rate and bend factors, respectively—determining the magnitude of the drying curve and its shape. It is postulated that the rate factor is a function of conditions external to the particles and that the bend factor is a function of particle size and species. Furthermore, an assumption that a and b are independent makes Eq. 6 essentially a one-parameter model that requires only an evaluation of the bend factor for the material being dried.

The bend factor has little influence on the drying rate because the drying time for each cascade is extremely short; therefore, only a rough estimate of its value is required. This study used the value $b = 0.75$, based on theoretical drying data generated by Kayihan (1982) for wood particles. The initial drying rate, $\dot{E}_o$, is defined by Rosen (1982) as:

$$\dot{E}_o = \frac{ab}{b\Gamma(b)} \tag{7}$$

Assumption 1 is that drying time, t, used in Eq. 6, is the time of particle fall within each drum segment, and assumption 2 is that temperature and moisture profiles are uniform within particles at the start of each fall. As a result, surface evaporation takes place at the start of each fall at a rate proportional to the wetted surface area of the particles. The initial drying rate is then evaluated as:

$$E_o = \frac{X_b}{X_{fsp}} \cdot \frac{UV_d(T_G - T_{wb})}{\lambda t_f S(X_o - X_e)} \tag{8}$$

As defined, the bound water moisture content may not exceed the moisture content at fiber saturation. Equation 8 assumes that all free water in wood voids is evaporated before any bound water is removed from wood cell walls. The fiber saturation point is a function of temperature. Bramhall (1979) proposed the following correlation:

$$X_{fsp} = 0.341 - 0.00133T \tag{9}$$

Simpson and Rosen (1981) give a function of temperature and relative humidity for estimating the equilibrium moisture content of wood:

$$X_e = \frac{K_1K_2(p_v/p_v^*)}{1 + K_1K_2(p_v/p_v^*)} + \frac{K_2(p_v/p_v^*)}{1 - K_2(p_v/p_v^*)} \cdot \frac{18}{W} \tag{10}$$

$$K_1 = 3.73 + 0.03642T - 0.0001547T^2$$

$$K_2 = 0.674 + 0.001053T - 0.000001714T^2$$

$$W = 216.9 + 0.01961T + 0.00572T^2$$

The volumetric heat transfer coefficient is derived under assumption 1 from an estimated coefficient of convective heat transfer of individual particles as follows:

$$U = \frac{hA_f}{V_d} \tag{11}$$

Calculation of the effective surface area of the particles in contact with the gas stream is based on the retention time analysis:

$$A_f = \frac{6}{D_p} H_d \frac{\rho_B}{\rho_p} \frac{t_f}{t_c} \tag{12}$$

By a method employed by investigators Ranz and Marshall (1952), Kuramae and Tanaka (1977), and Hirosue and Shinohara (1978), the coefficient for surface-film convective heat transfer of individual particles may be estimated from the Nusselt number correlation for spherical particles:

$$Nu = 2 + 0.6Re^{0.5}Pr^{0.33} \tag{13}$$

The Reynolds number in Eq. 13 is based on a particle velocity vector composed of both a horizontal and vertical component relative to the velocity of the moving gas stream.

SOLUTION PROCEDURE

A computer program, Rotary Dryer Simulation (RDS), generated from the model developed in this study, has the capability to predict retention time, gas temperature, and particle moisture content at any point along the dryer length. RDS is initiated by establishing the conditions at the dryer inlet: gas flow rate; temperature and composition; amount of air leakage; and particle flow rate, temperature, moisture content, and size. The gas temperature of the outlet of each drum segment is estimated. From the mean gas temperature of a segment, viscosity, specific heat, thermal conductivity, and density are then evaluated.

A retention time analysis is performed for the first drum segment. Reevaluation of retention time variables of subsequent segments may be required if gas properties and particle moisture content change sufficiently. New retention time variables are also required if a change in the flighting configuration is encountered along the drum. The variables calculated for each segment are holdup, time of particle fall, distance of particle fall, and retention time.

The amount of drying within the drum segment is calculated with Eq. 6 from the mean gas and particle properties. Equations 1, 3, and 4 are then solved simultaneously to arrive at gas humidity, gas temperature, and particle temperature at the drum-segment outlet. The calculated outlet gas temperature is compared to the gas temperature estimated earlier, which was used for determining gas properties within the segment. If the values do not sufficiently agree (±2%), the calculated value is used for a new estimate, and an iteration of the calculations for the drum segment is performed. If the values agree, the drum is checked to see if the end has been reached. Outlet conditions of one segment are used for inlet conditions of the next, and the procedure is repeated until the end of the drum is reached.

The output from RDS includes a complete listing of the gas and particle conditions for each drum segment and a summary of the retention time variables along the drum length. A source code listing of RDS is given by Kamke (1984).

EXPERIMENTAL

The purpose of the rotary-drying experiment was to obtain a range of temperature and moisture-content profiles for both gas and particle streams along the length of the dryer. Six test runs were made with the system used in the retention time study (Figure 2). Test data were then compared to predictions made by the RDS computer program.

Measurements of gas temperature were taken at point E (Figure 2) with a shielded thermocouple, and at points G, H, I, and J inside the drum with three-wire resistance temperature detectors. Output from each of the latter was routed through a rotary coupling at the exit end of the drum. Outlet gas temperature was measured with a series of five resistance temperature detectors mounted in the drop-out hopper and

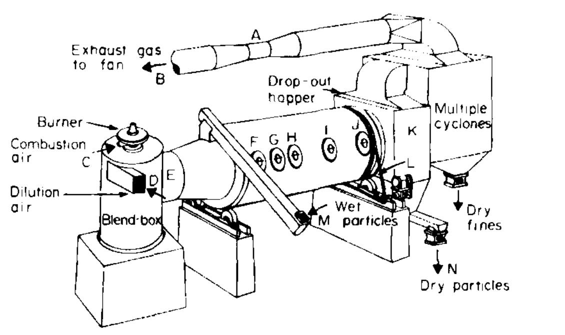

Figure 2. A single-pass rotary dryer with centerfill flights used for retention time and drying experiments.

arranged diagonally to the drum cross section. Wet-bulb and dry-bulb temperatures were taken at the fan, point *B*.

The total gas flow exiting the drum was measured by a venturi at point *A*. Air leaks after the drum outlet were assumed to be negligible as the outlet rotary seal was in good working order and the outlet particle screw-feed conveyor and multiclone separator were equipped with rotary air locks. Combustion air flow (point *C*) and dilution air flow (point *D*) were measured with a standard pitot tube traverse. Air leakage was calculated from these measurements, the metered fuel flow rate, and the measurements of evaporated moisture from the wood.

Gas samples were extracted at points *E* and *K* for determining the oxygen and carbon dioxide content. An Orsat volumetric analysis was made by means of chemical absorption of a gas sample in a portable Fyrite tube device. These measurements were used to support calculations of air leakage with a component-material balance for oxygen and carbon dioxide over the entire drum.

Outside wall temperatures of the drum, measured with an infrared pyrometer at points *F*, *G*, *H*, *I*, and *J*, were used for estimating heat loss through the drum wall.

Inlet and outlet wood-particle samples of each test run were taken for later determination of moisture content by an oven-drying method. In-line infrared moisture meters continuously monitored particle moisture content at the inlet and outlet. Particle temperatures were also obtained at the inlet and outlet. Thermocouples were placed in the moving particle bed at the conveyor belt inlet and in a specially constructed damper apparatus inside the drop-out hopper.

Wood particle samples and temperature measurements were taken along the drum length at access ports *F*, *G*, *H*, *I*, and *J*, which were fitted with a removable sampling device that rotated with the drum (Figure 2). The sampling device contained a fine wire thermocouple and plunger assembly such that the particle sample could be compressed for good contact with the thermocouple and easily removed later for moisture-content determination.

All six test runs were conducted in one day. An initial warmup period of about 2 h was required before the first run. Steady state operation was assumed when the exit-particle moisture content did not change by more than 1% over a 15 min time span. Each test run required about 30 min of steady state operation.

RESULTS AND DISCUSSION

A summary of the rotary-drying test results is shown in Table 1. The inside-drum gas temperatures were calculated from measured flow rates, particle moisture content, particle temperature, and the outside-drum wall temperature. The measured inside-drum gas temperatures were inconsistent because of nonhomogeneous gas flow. Similar problems with measuring inside-drum temperatures have been previously reported (Friedman and Marshall, 1949; Saeman and Mitchell, 1954; Tscheng and Watkinson, 1979).

Gas flow measurements were checked by means of a component material balance from the oxygen and carbon dioxide measurements. Whereas agreement was not perfect, the comparison supported the results of the gas flow measurements within the accuracy of the sampling procedure. Dilution air flow corresponded well with that in past experience with this rotary dryer. Measurements of dilution air flow were used to calculate the blend-box gas temperature. Agreement between calcu-

Table 1. Summary of Rotary Dryer Test Results*

	Test Run					
	1	2	3	4	5	6
Gas Flows, kg/s						
Total gas, Point *A*	1.66	2.04	1.94	1.93	1.54	1.54
Gas Temperatures, °C						
Drum inlet	161.8	156.7	200.7	212.0	267.3	247.3
Point *G*	100.9	114.1	135.2	146.4	173.3	135.9
Point *H*	87.5	102.0	115.9	123.7	143.5	112.7
Point *I*	74.8	85.8	87.3	99.9	118.5	83.3
Point *J*	75.2	79.7	75.7	88.3	107.8	75.6
Drum outlet, Point *K*	62.4	64.2	65.5	74.5	96.5	65.0
Particle Temperatures, °C						
Inlet screw-feed conveyer, Point *M*	18.6	17.7	18.9	21.3	23.4	24.1
Point *F*	41.5	43.3	50.1	41.4	42.0	42.4
Point *G*	47.6	49.5	54.5	49.4	49.2	48.0
Point *H*	45.0	45.5	53.0	49.6	50.0	48.4
Point *I*	42.3	43.9	52.5	48.3	48.8	48.6
Point *J*	36.8	38.6	47.2	41.4	46.1	44.5
Drum outlet, Point *L*	33.7	38.6	52.3	49.3	44.5	51.9
Particle Moisture Content, dry basis						
Inlet screw-feed conveyer, Point *M*	1.401	1.405	1.425	1.399	1.390	1.352
Point *F*	1.192	1.247	1.136	1.110	1.053	0.947
Point *G*	0.987	1.057	0.887	0.875	0.779	0.671
Point *H*	0.857	0.925	0.658	0.658	0.552	0.498
Point *I*	0.731	0.743	0.403	0.418	0.357	0.267
Point *J*	0.727	0.668	0.276	0.295	0.266	0.201
Drop-out hopper, Point *N*	0.603	0.497	0.173	0.160	0.170	0.122
Outside Drum Wall Temperatures, °C						
Point *F*	33.0	37.7	56.2	57.9	58.3	61.8
Point *G*	40.4	43.8	58.6	60.0	61.3	64.5
Point *H*	27.2	32.6	44.3	47.3	47.9	49.7
Point *I*	23.2	28.7	40.5	44.1	44.1	45.2
Point *J*	21.1	25.2	37.7	40.0	40.4	42.5
Drum Operation						
Drum speed, rpm	5.5	5.5	5.5	2.8	2.8	5.5
Dry particle feed rate, kg/hr	280	283	283	286	286	294

* See Figure 2 for point locations.

lated and measured blend-box gas temperatures was good, which shows that gas flow measurements are probably a good indicator of actual flow conditions.

Results from the rotary-dryer experiment were compared to a set of rotary-dryer simulations generated by the RDS computer program. Drying profiles of the predicted gas temperature, particle temperature, and particle moisture content were plotted with measured values taken along the drum length (Figure 3). The predicted profiles follow the same trends as their measured counterparts. Agreement is good and consistent throughout the drum length.

The accuracy of the predicted rate of heat transfer must be conjecture without the aid of experimental evidence. The predicted volumetric heat transfer coefficient is close to values reported in the literature, but different rates of heat transfer could yield identical profiles of gas temperature and particle moisture content if the retention times were also different. A high rate of heat transfer for a short time could yield a result identical with a low rate of heat transfer for a long time. Solid conclusions must be supported with data for both retention time and heat transfer.

The implications of assumptions 1 and 2 should also be considered, as these conditions restrict the time for drying to the period of particle fall. At the end of travel on the lifting flights, the particles are assumed to be uniform in moisture content and temperature because of the relatively long time for internal movement of moisture and heat. Certainly particles may dry as they ride on the lifting flights, particularly those exposed on the surface of the particle bed. However, calculations suggest that the amount of heat transfer on a particle surface during lifting is insignificant to the amount during fall (Kuramae and Tanaka, 1977; Kamke, 1984). As yet there is no experimental evidence to support these calculations.

The effect of an erroneous retention time prediction can be evaluated from results of the retention time measurements in Part I of this study. Degrees of error in the retention time prediction depended on particle size and drum speed. For the weighted mean particle size used in the rotary dryer experiment, a linear interpolation was performed for estimating the expected error in the prediction at two drum speeds. These values were then averaged, yielding an expected overestimate in the prediction of 3.2%. Additional computer simulations were made with an adjustment for the expected error in the retention time predictions. This small adjustment did not significantly affect the predicted drying profiles.

Predictions for particle temperatures were good for the first four test runs. Predicted temperatures increased at a decreasing rate near the drum inlet to a value slightly above the wet-bulb temperature, then remained fairly constant. If the particles were dried well above fiber saturation, the predicted particle temperature dropped as the particles approached the drum exit. If the particles were dried below fiber saturation, as predicted in test runs 5 and 6, the temperature increased nearer the drum exit.

The predicted particle temperatures in test runs 5 and 6 were too high throughout the length of the drum, a result of an overestimated rate of heat transfer to the particles. As the heat capacity of the particles is small in relation to the evaporative load, a small error in the predicted rate of heat transfer would result in a large error in the predicted particle temperature. This effect would be most prevalent near the drum inlet, where the heat transfer rate is greatest.

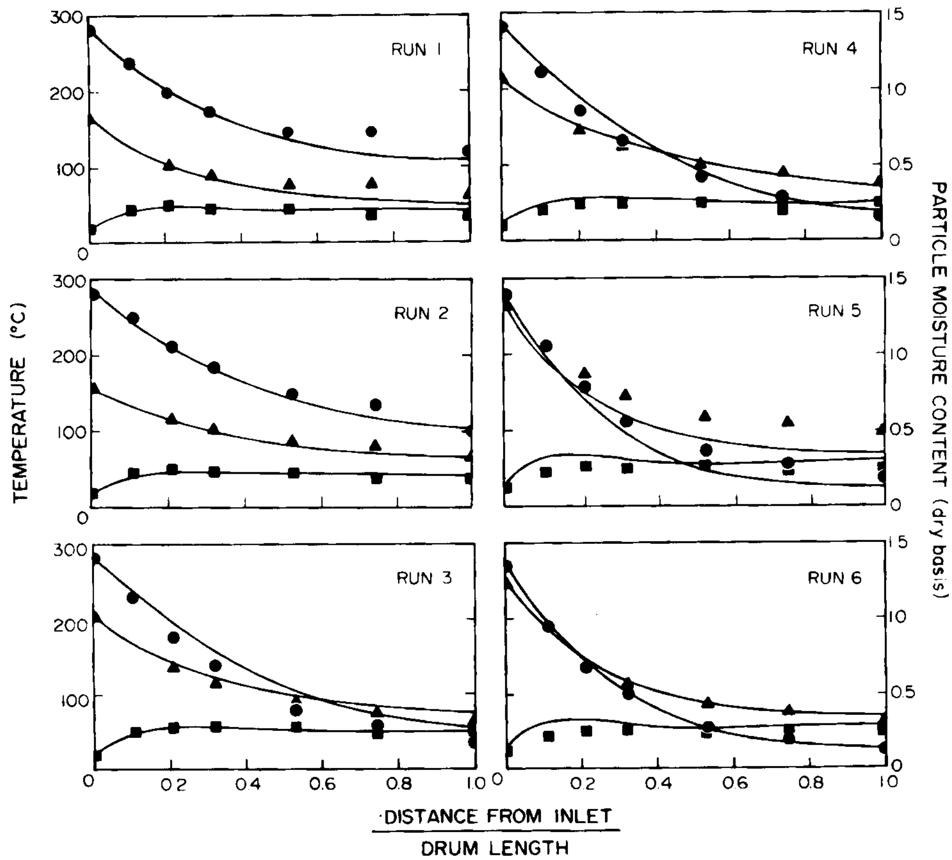

Figure 3. Comparison of results of the rotary dryer simulation ——— with measured results of six test runs: ▲ gas temperature, ■ particle temperature, ● particle moisture content.

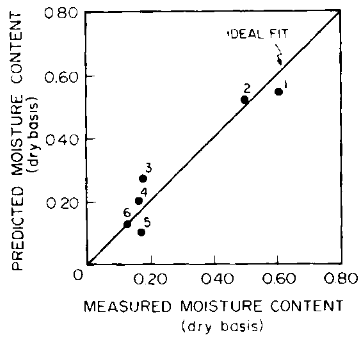

Figure 4. Predicted and measured moisture content of outlet particles in the rotary dryer, six test runs.

Predicted gas-temperature profiles are closely associated with the predicted moisture content of particles, as material and energy balances must be satisfied throughout the drum. In all test runs, the heat loss through the dryer wall and the sensible heat load of the particles were small in comparison to the evaporative load. Therefore, underestimation of the drying rate resulted in a corresponding overestimation of the gas temperature.

Figure 4 is a plot of the predicted moisture content of outlet particles with the measured values for all test runs. The overall root mean square error for all runs is 22.2%. Probably most of this error is associated with the predicted rate of heat transfer.

SIMULATION TRIALS

Many factors influence drying behavior in a rotary dryer. Figure 5 summarizes predicted effects of some selected independent parameters on particle moisture content at the outlet. The base conditions for all comparisons were from test run 2. Each variation from the base condition, plus and minus 50%, was simulated while all other conditions were held constant.

Within the range of conditions examined, inlet particle moisture content had the greatest affect on the predicted outlet particle moisture content. Next, in decreasing order of importance, were blend-box gas temperature, drum diameter, air leakage, drum length, gas volumetric flow rate, particle size, particle sphericity, drum speed, angle of repose, and bend factor.

Of special interest is the effect of the gas volumetric flow rate. Both positive and negative variations from the base case caused a reduction in drying, which indicates that there is an optimum value. The peak occurs as a result of the combined effect of the gas flow rate on the particle drag force and on the convective heat transfer coefficient. Increased gas flow causes a particle to pass through the drum with fewer cascades; however, it enhances the convective rate of heat transfer. These counteracting effects on the drying indicate that an optimum gas flow rate must exist.

Also of note is the bend factor effect of Rosen's (1982) wood-drying model. Internal diffusion has small effect on the extent of drying in a rotary dryer because the soaking periods are long, relative to drying periods, within the range of conditions studied. This would seem to justify overlooking the effects of internal temperature and moisture gradients within the rotary-dryer simulation. Accounting for internal diffusion through the use of an empirical drying model is adequate.

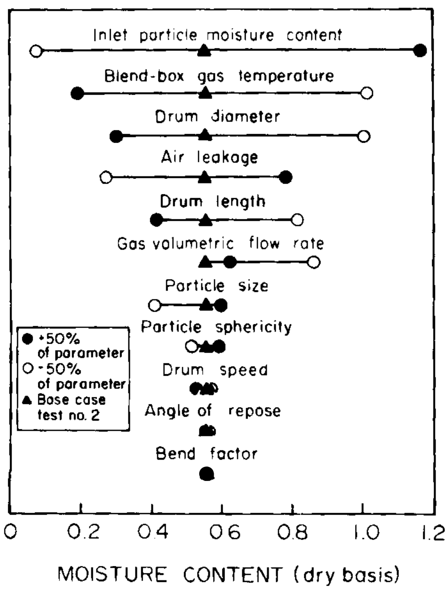

Figure 5. Effect of variations of selected rotary-dryer parameters on the predicted moisture content of outlet particles.

NOTATION

a = rate ractor
A = area, m^2
b = bend factor
c = specific heat, J/kg · °C
D = diameter, m
$\dot{E}_o$ = initial drying rate, 1/s
G = dry gas mass flow rate, kg/s
h = surface-film convective heat transfer coefficient, J/s · m^2 · °C
H = drum holdup, m^3
K = empirical constant in Eq. 2
L = length, m
Nu = Nusselt number
P = partial pressure, Pa
Pr = Prandtl number
Q_S = rate of heat transfer to particles, J/s
Q_L = rate of heat loss through drum wall, J/s
R = thermal resistance, °C/W
Re = Reynolds number
S = dry solids feed rate, kg/s
t = time, s
T = temperature, °C; K in Eq. 10
U = volumetric heat transfer coefficient, J/s · m^3 · °C
V = volume, m^3
X = particle moisture content, dry basis, kg/kg
Y = gas moisture content, dry basis, kg/kg

Greek Letters

Γ = gamma function
$\Delta T_{\ell m}$ = logarithmic mean temperature difference, °C
λ = latent heat of vaporization, J/kg
ρ = density, kg/m^3

Subscripts

A = air
B = bulk
b = bound water
c = cascade
d = drum
e = equilibrium

f = particle fall
fsp = fiber saturation point
G = gas
o = initial
p = particle or solids
ref = reference condition
S = dry solids or particles
T = total
v = water vapor
w = liquid water
wb = wet-bulb

Superscripts

s = saturated

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