Mathematical Simulation of Corn Drying — A New Model

T. L. Thompson, R. M. Peart and G. H. Foster
Assoc. Member ASAE Member ASAE Member ASAE

DRYING is a continuous process with changes in moisture content, air and grain temperature, and the humidity of the air all occurring simultaneously. In fact, these changes vary for different drying methods and for different locations in the drying bed. The objective of the study reported in this paper was to develop a mathematical procedure whereby grain-drying predictions could be made with infinitely many sets of drying conditions and with nonconventional as well as conventional convection grain-drying methods. The mathematical drying model developed incorporates many of the factors that affect grain drying, and is capable of determining the effect of many drying parameters on the drying results, especially with high-temperature drying.

For this study, the basic approach used to describe the continuous drying process was to divide the process into many small processes and simulate them by consecutively calculating the changes that occur during short increments of time. The basic simulation approach used was to calculate the drying performed on a thin layer of grain and then combine many thin layers to form the grain bed. This approach permits complete simulation of less conventional drying methods such as concurrent flow (parallel) and counterflow, as well as crossflow drying methods.

The simulation model described in this paper (11)* can be used to predict the results of any of these drying methods and also predict transient results (such as humidity of the air, equilibrium moisture content, and many others) throughout the process. Of course, computer capability is necessary, but present-day computer technology makes this type of solution feasible and practical. An advantage of this type of computer simulation is that, when new truths are learned about the drying process, it would be a simple matter to incorporate them into the simulation model.

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The authors—T. L. THOMPSON, R. M. PEART and G. H. FOSTER—are associate professor of agricultural engineering, University of Nebraska, Lincoln; professor of agricultural engineering, Purdue University; and agricultural engineer, transportation and facilities research division, ARS, USDA. Approved for publication as paper No. 3213 of the journal series of the Purdue University Agricultural Experiment Station.

* Numbers in parentheses refer to the appended references.

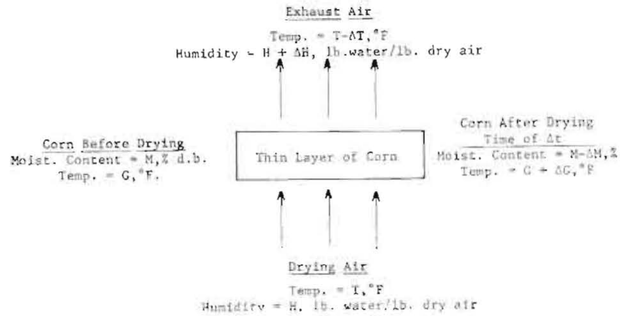

FIG. 1 Schematic diagram of basic simulation approach.

The following sections develop this mathematical drying model. A thorough understanding of the changes that occur during the drying of a thin layer of grain is necessary before predictions can be made about deep bed drying. If calculations can be made describing these changes, then groups of thin layers can be combined to form the deep bed.

Thin Layer Drying

Briefly, the drying of a thin layer of grain was simulated by considering the changes that occur in the corn and the drying air as shown in Fig. 1.

Drying air (T deg F, H lb water per lb dry air) is passed through a thin layer of corn (M percent moisture, G deg F temperature) for a drying time interval, Δt. During this interval ΔM percent moisture is evaporated from the corn into the air increasing its absolute humidity to H + ΔH lb water per lb dry air. During drying the temperature of the drying air is decreased (ΔT deg F) in proportion to the temperature increase of the corn (ΔG deg F) and the evaporative cooling accompanying the moisture evaporation. The amount of drying performed was calculated by a thin-layer drying equation with constants dependent on the drying air temperature. Complete heat balances were used to calculate the final air and grain temperature consistent with the evaporative cooling accompanying the moisture evaporation and with the initial temperature of the drying air and the grain. A detailed analysis of these calculations follows. The reader who is not interested in the details of the model, may refer directly to the section on "deep bed drying" without any loss of continuity.

The following assumptions or relationships were used in the development of the mathematical model; justification and the development of each relationship follow the statement:

Assumptions

1 Fully exposed, thin-layer drying is represented by the equation:

$$t = A \ln (MR) + B [\ln(MR)]^2$$

where

$A = -1.862 + 0.00488\ T$

$B = 427.4\ e^{-0.033T}$

t = time to dry to MR with drying temperature T, hr

MR = moisture ratio, $\dfrac{M - M_e}{M_o - M_e}$

M = moisture content at time t, percent dry basis

M_o = initial moisture content, percent dry basis

M_e = equilibrium moisture content, percent dry basis

Henderson and Perry (3) reported that during the falling-rate drying period, the moisture removal rate is inversely proportional to the moisture to be removed or $\dfrac{dM}{dt} = -k(M - M_e)$. Solution of this equation yields the simple exponential drying equation $MR = e^{-kt}$.

Most investigators state that the drying constant k is dependent on the drying air temperature, but they do not explicitly specify the relationship. The following experimental investigation was performed to determine drying constants and this relationship for yellow-dent shelled corn.

A series of thin-layer drying tests was performed in the agricultural en-

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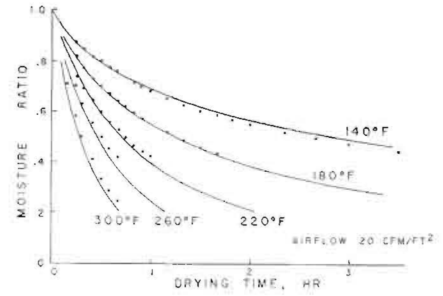

FIG. 2 Predicted (curves) versus experimental (points) thin-layer drying results.

gineering processing laboratory at Purdue University during the fall of 1963. The tests were performed in an experimental thin layer dryer. The dryer consisted of a fan blowing heated air through a screened bottom tray holding a sample of corn.

The main variable investigated in the test series was drying air temperature. A few other exploratory tests were performed to evaluate the effect of airflow rate and corn variety on drying rate.

Throughout the drying tests, the moisture in the corn was measured by periodically weighing the corn sample. This enabled the moisture removal rate to be evaluated. Each drying test was terminated when the moisture was reduced to a safe storage level (12 percent w.b.). Tests were performed with 19, 23, and 33 percent w.b. initial moisture corn, 20 and 60 cfm/ft² of drying air, and with temperatures ranging from 120 to 340 F.

The results from each drying test were analyzed by fitting the experimental data to two types of assumed drying equations. One of these was the simple exponential drying equation: $MR = e^{-kt}$. Plots of the experimental data versus the best fit of the assumed equation showed that the simple exponental equation did not adequately represent the experimental results.

The second drying equation used was a second-order exponential curve (parabola on semilog paper). This equation had the form:

$$t = A \ln(MR) + B (\ln(MR))^2$$

The results from the test series showed that dry-air temperature was the main variable that affected the drying rate. The other variables, corn variety and airflow rate, did not significantly affect the drying constants for the values investigated. From this it was assumed that the air flow rates, in the range considered, had a negligible effect on the drying equation. The results (constants A and B versus drying air temperature) from the test series were plotted and analyzed by the method of least squares to obtain an equation to represent thin layer drying for the range of drying temperatures investigated. The results showed that constants A and B from the second order equation followed the form:

$$A = -1.862 + 0.00488\ T$$

and

$$B = 427.4 \exp(-.033\ T).$$

A comparison between the experimental drying results and those predicted by the above equation is made in Fig. 2 for five drying-air temperatures. The plot shows a reasonable representation of the experimental results for the wide range of temperatures used.

2 It was assumed that the kernel temperature of the corn was equal to the air surrounding the kernels, after accounting for the cooling effect of moisture evaporation and different initial corn and air temperatures.

Thompson and Foster (10) and Henderson and Pabis (4) reported on the air-grain temperature relationship of grain. Thompson and Foster determined exposed cooling rates for dry corn. They found that, when warm dry grain in a thin layer was exposed to relatively large volumes of cool air, it requires about 48 seconds to cool the grain nine-tenths of the way to the cooling-air temperature. Henderson and Pabis measured the temperature in the center and at two points on the surface of a kernel. When this kernel was subjected to heated-air convection drying, the difference in temperature between the center of the kernel and the surface was significant (measurable) only during the first three or four minutes.

From these results it is apparent that the heat transfer between a corn kernel and the surrounding air is very rapid and that the temperature of the corn rapidly approaches the temperature of the air immediately surrounding the kernels. This is consistent with the fact that average kernel temperature in a dryer is less than the drying air temperature in the plenum, because the air temperature decreases as it passes through the corn.

3 It was assumed that corn equilibrium moisture content for a given air state point is represented by:

$$1 - RH = \exp(-c\ (T+50) M_e^n) \quad \text{. . . . . [2]}$$

where

$c = 3.82 \times 10^{-5}$

$n = 2.0$

RH = relative humidity.

Equilibrium moisture content is one of the factors that determines the rate of moisture removal from a layer of corn and establishes a lower limit to which the corn can dry. The temperature and relative humidity of the air surrounding the kernel determines its equilibrium moisture content. Henderson (2) developed the following empirical equation to represent the equilibrium curves:

$$1 - RH = \exp(-c\ (T+460) M_e^n)$$

where

$c = 1.10 \times 10^{-5}$

and

$n = 1.90.$

A comparison of the equilibrium moisture of shelled corn as determined by this empirical equation and a plot of the equilibrium moisture content as experimentally determined by Rodriguez-Arias (7) for approximately the same temperatures showed a greater effect due to temperature than the empirical equation and constants indicated.

The constants in the empirical equation were varied (and analyzed on the digital computer) until the equation represented the experimental results of Rodriguez-Arias more accurately. The constants for the empirical equation that represent the experimental results the best (of those constants investigated) are: $c = 3.82 \times 10^{-5}$, $n = 2.0$, with the temperature factor $(T + 460)$ replaced by $(T + 50)$.

Strohman (8) studied the thermodynamic properties of water in corn and developed the equation: $RH = \exp(a e^{bM} \ln Ps + c e^{dM})$, where $a = 0.776$, $b = -0.113$, $c = -6.61$, and $d = -0.190$, to represent the equilibrium relative humidity of corn at various moisture contents. This equation is valid over the whole range of moistures, relative humidities, and temperatures. Data from Rodriguez-Arias (7) was used to develop this equation. The equation was not used in the mathematical drying model developed in this report because it was impossible to solve directly for the equilibrium moisture content, M.

The following procedure was developed to determine the relative humidity of the drying air given the air temperature and absolute humidity. Relative humidity is defined as the ratio of the actual water-vapor pressure and the saturated-vapor pressure at the given air temperature. Using a table of saturated vapor pressures versus temperature (6) and a table of absolute humidities at different dew point temperatures (1), the relative humidity was determined by finding the dew point temperature corresponding to the absolute humidity and finding the ratio of the saturated vapor pressure at the dew point temperature and the saturated vapor pressure at the air temperature. The relative humidity of the air is this ratio. A Fortran subprogram was written to perform this calculation.

4 The latent heat of water in corn was assumed to be represented by the equation:

$$L' = (1094 - 0.57T)\ (1.0 + 4.35e^{-28.25M}) \quad [3]$$

The data of Thompson and Shedd (9) was fitted to the equation: $\frac{L'}{L} = 1 + ae^{-bM}$ by the method of least squares. The equation, $L = 1094 - 0.57\ T$, for the latent heat of water (3) and the results from the least squares analysis resulted in the above equation. It was based on experimental data in the 10 to 15 percent w.b. region. The authors feel that extrapolation of this equation was justified, because for higher moisture contents the heat of vaporization approached that of free water and for lower moistures it became increasingly difficult to evaporate water from the corn kernel.

5 The specific heat of corn was assumed to be represented by the equation:

$$c = 0.350 + 0.00851\ M_w \quad [4]$$

where M_w = moisture content percent wet basis.

Kazarian and Hall (5) found that the specific heat of soft white wheat and yellow dent corn was linearly dependent on the moisture content. From their experimental evaluations on yellow dent corn, they determined the above equation.

Thin Layer Simulation

The remainder of this section on thin layer drying is a development of a procedure to calculate the *average* changes during drying when a thin layer of corn is dried for a time increment Δt. The drying process was considered to be divided into separate processes (including temperature equilibrium between the grain and air, moisture removal, and evaporative cooling of the air and the grain) for this development and the resulting calculations. These processes actually occur simultaneously, but the process was divided up to simplify the simulation. The heat balances were written in terms of Btu per lb of dry air flowing through the layer. A grain-to-air ratio was used to convert the specific heat of corn to these units.

Prediction of the amount of drying that occurs in a thin layer of corn can be made by considering the initial air and grain conditions, using a thin-layer drying equation and complete heat balances to predict the final air and grain conditions.

Drying-Air Temperature

The equilibrium temperature of the drying air and the corn was calculated by performing a sensible heat balance and was used as the drying-air temperature. Drying-air temperature as used here is the temperature of the air at the drying layer and should not be confused with the temperature of the heated air before it enters the drying column. This heat balance is only an intermediate calculation to determine the drying air temperature and does not include moisture evaporation. Normally the corn does not attain this temperature since evaporative cooling accompanies the sensible heat transfer.

For the heat balance, the specific heat of corn was converted to Btu per lb air deg F.

Thus $C = (0.350 + 0.00851\ M_w)\ R$ where R = air-to-grain ratio, lb air per lb corn.

The equilibrium temperature of the corn and the air before drying was determined with the following heat balance:

$$0.24\ T_o + H_o\ (1060.8 + 0.45\ T_o) + C\ G_o = 0.24\ T_e + H_o\ (1060.8 + 0.45\ T_e) + C\ T_e,$$

where the subscript o refers to original and e to equilibrium values of air temperature, T, grain temperature, G, and absolute humidity, H.

The first two terms on each side of the equation represent the initial and equilibrium heat content of the air, and the third terms are the initial and equilibrium heat content of the corn. Solving this equation for the unknown equilibrium temperature:

$$T_e = \frac{(0.24 + 0.45\ H_o)\ T_o + C\ G_o}{0.24 + 0.45\ H_o + C} \quad [5]$$

Moisture Removed

The equilibrium moisture content, M_e, of the corn was calculated by determining the relative humidity of the air and using the equilibrium temperature from the above heat balance in the equilibrium moisture content equation. Thus

$$M_e = \left[\frac{-ln\ (1 - RH)}{(3.82 \times 10^{-5})\ (T_e + 50)}\right]^{0.5} \quad [6]$$

In a deep-bed drying process the drying air temperature, T_e, at one location in the bed usually changes as drying progresses. A new drying curve is specified when the drying temperature changes, and the amount of drying on the old curve has to be transformed to the new curve. This transformation was made by calculating an "equivalent drying time." This was calculated with the drying equation:

$$t = A\ ln(MR) + B\ (ln(MR))^2$$

using the new values of A, B, and MR (calculated with the new M_e and the present M). This is the equivalent time that would be needed on the new curve to dry to the present moisture content. The moisture ratio at the end of the present drying period was calculated by solving the thin layer drying equation for MR and using a time, t, of the equivalent drying time plus the drying time interval Δt. The final moisture content of the layer was then calculated from the moisture ratio.

Final Air and Grain Temperature

The final air and grain state points consistent with the amount of drying performed on a thin layer of grain during time interval were calculated by the following procedure:

$(M_o - M_f)$ percentage points of moisture were removed from the corn and evaporated into the air; thus the absolute humidity of the air was increased by an amount

$$\Delta H = \frac{(M_o - M_f)\ R}{100}, \text{ and}$$

$$H_f = H_o + \Delta H$$

The final temperature was determined with the following heat balance:

$$0.24T_e + H_o(1060.8 + 0.45T_e) + CG_e + \Delta H(G_e - 32) = 0.24T_f + H_f(1060.8 + 0.45T_f) + CT_f + \Delta L\ \Delta H,$$

where $G_e = T_e$ from equation [5].

The first two terms on each side of the equation are the initial and final heat content of the air; the third term is the initial and final heat content of

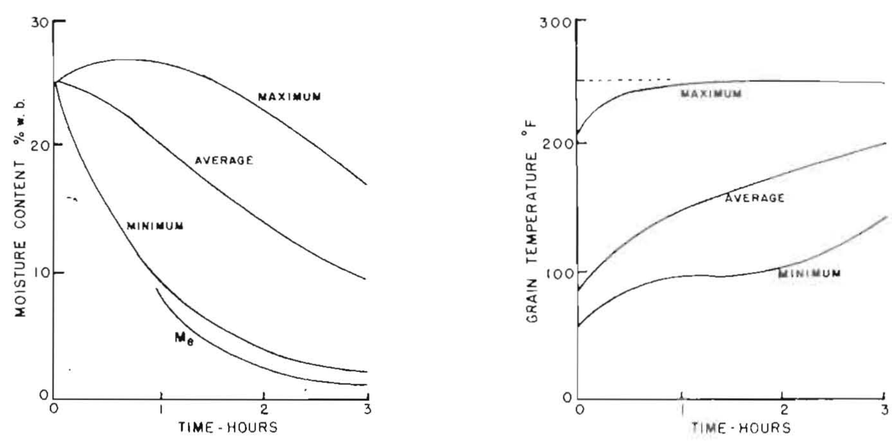

FIG. 3 Crossflow dryer. Drying temperature, 250 F; air flow, 60 cfm per sq ft; depth, 2 ft M_o = 25 percent wet basis.

the corn. The fourth term on the left side of the equation is the heat content of the water that was evaporated, and the last term in the equation is the heat of vaporization required to evaporate moisture from the corn above that required to evaporate the same amount of free water.

Solving, $$T_f = \frac{(0.24 + 0.45H_o)T_e - \Delta H(1060.8 + \Delta L + 32 - G_o) + CG_e}{0.24 + 0.45H_f + C} \quad [7]$$

is the final air and grain temperature for the layer.

Infeasible Air State Points

After each one of the heat balances, it was necessary to determine if the temperature and absolute humidity of the air was feasible (if the relative humidity as mathematically determined was less than 100 percent). If the state point was infeasible, it was necessary to perform another heat balance and simulate the condensing of water from the air into the corn.

From the infeasible state point (represented by H_o, G_o, and T_o), a heat balance was written between original and final conditions for the incremental drying period:

$$0.24T_o + H_o(1060.8 + 0.45T_o) + CG_o + (H_f - H_o)(G_o - 32) = 0.24T_f + H_f(1060.8 + 0.45T_f) + CT_f$$

This heat balance has two unknowns — the final temperature, T_f, and the exhaust humidity, H_f. Interpolation was used on the relative humidity versus temperature relationship to converge to a relative humidity of 100 percent and to determine H_f and T_f. Using a method developed to find the zero of unknown functions (13), this interpolation required only three or four trials to obtain a relative humidity between 99 and 100 percent. The water that was removed from the air was condensed into the corn, or:

$$M_f = M_o - \frac{100(H_f - H_o)}{R} \quad [8]$$

The above description of the mathematical drying model presents the steps that were necessary to calculate the final air and grain conditions after drying for a time interval Δt on a single layer of corn.

All of the steps presented in this section were combined into a common computer subprogram that was used with each one of the deep-bed drying models.

Deep-Bed Drying

Crossflow Dryer

Theoretically, a crossflow dryer operates by passing warm air through a static bed of grain. The drying air evaporates moisture from the corn and carries it away. As the air absorbs moisture, its temperature decreases and its ability to pick up more moisture decreases. Considering a batch-type crossflow dryer to be a group of thin layers of corn stacked one upon another with the drying air blowing up through the stack, the mechanisms of this dryer type were simulated by calculating the air and moisture changes as the drying air passed from one layer of corn onto the next. Each layer was dried for a short time interval using the exhaust air from one layer as the input drying air to the next. The process was then repeated with a second, third, . . ., drying time interval until the average final moisture was as desired.

Assuming no appreciable mixing, a continuous crossflow dryer operates the same as the batch-type dryer just described. Infinitely long layers of corn pass through the dryer, with the drying air flowing in a direction normal to the corn layers. The air passes from one layer of corn onto the next. The time that each kernel is subjected to the drying air and the depth of the group of thin layers are the two variables used to calculate the grainflow rate through the dryer.

Fig. 3 shows the results of a typical crossflow simulation. In a crossflow dryer the kernels on the air input side are overdried and those on the exhaust side are underdried when the average moisture content is at the desired level. Normal practice is to mix all of this grain together to obtain the desired final moisture. The average equilibrium moisture content, to which the air could dry the grain, decreases as the corn dries.

Concurrent-Flow Dryer

With a concurrent-flow dryer the drying air and the corn travel through the dryer in the same direction. Again considering the grain in the dryer as a group of thin layers with the drying air blowing down through the layers consecutively, and visualizing that at each time interval a new layer is placed on the top of the stack and a layer is removed from the bottom, the concurrent-flow drying process can be simulated. If the layer that was in the i^{th} position during the j^{th} time period is in the $n+1^{st}$ position in the $j+1^{st}$ time period, the process can be simulated very easily. The simplified simulation procedure consists of calculating the moisture changes of one layer as it travels through the dryer. In other words, if the time interval is properly selected, the exhaust air from a layer in the first position during the first time period is the input to the same layer which is in the second position during the second time period and so forth until the desired depth is obtained.

This simulation represented the equilibrium or steady-state concurrent flow drying process with the given initial air and grain conditions and for a prespecified grainflow rate. For a given depth, the grainflow rate determined the final moisture content. A method for finding the zero of unknown functions (13) was used to determine the grainflow rate necessary to dry to the desired final moisture.

Fig. 4 shows the results of a typical concurrent flow simulation. These results show that, as the grain moves through a concurrent-flow dryer, most of the moisture is removed during the first ½ foot of travel and then the process has a built-in tempering period which decreases the drying stress in the kernel. Basically, the process consists of the corn giving off moisture to the drying air which cools the air and the corn. As the corn gives off moisture and the air cools, the relative humidity of the air increases and thus the equi-

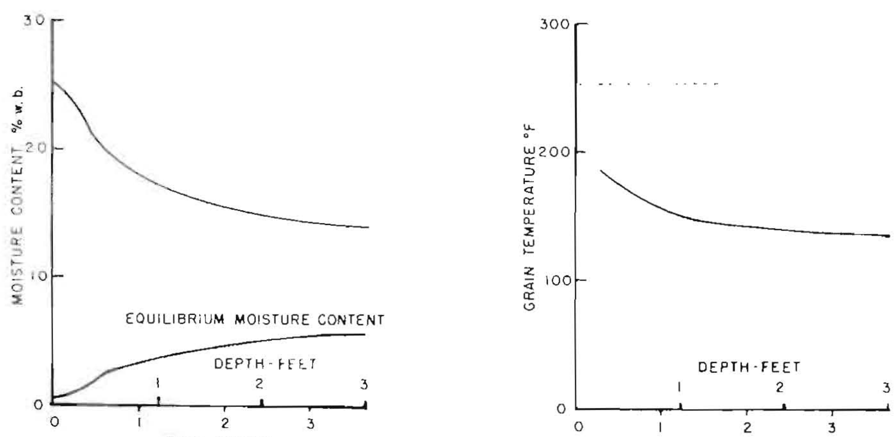

FIG. 4 Concurrent-flow dryer. Drying temperature, 250 F; airflow, 60 cfm per sq ft; M_o = 25 percent wet basis.

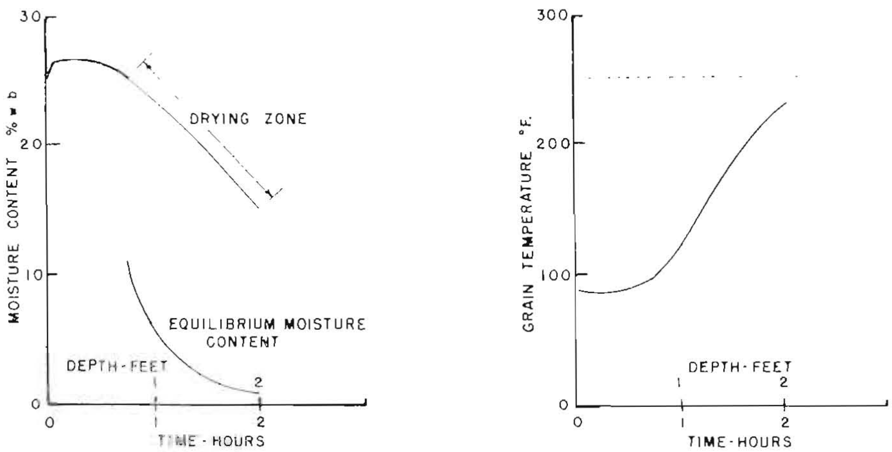

FIG. 5 Counterflow dryer. Drying temperature, 250 F; airflow, 60 cfm per sq ft; M_0 = 25 percent wet basis.

librium moisture content increases, which slows down the rate of drying. A plot of the equilibrium moisture content versus depth in a concurrent-flow dryer is also shown. With a concurrent-flow dryer, the hot drying air immediately comes in contact with the cool wet corn. The drying air is almost immediately reduced in temperature and the initial moisture that is removed during the first few minutes of drying further reduces the drying temperature. To summarize, with concurrent-flow drying, the air and grain temperatures approach each other in the first few inches of drying, then gradually decrease as the corn moves through the dryer.

Twenty-six concurrent-flow drying tests were performed in a laboratory dryer during the 1964 and 1965 drying seasons (11). The results from these tests will be presented in another report (12). The results of these tests were very similar to the simulated results as shown by Fig. 4.

Counterflow Dryer

With a counterflow dryer the drying air and the corn travel through the dryer in opposite directions. Again considering the grain in the dryer as a group of thin layers with the drying air blowing up through the layers and envisioning that at each time interval a new layer is placed on the top of the stack and a layer is removed from the bottom, the counterflow process can be simulated. An iterative solution of this process was necessary because sufficient initial conditions were not known to simulate its performance directly. At the top of the dryer, the state point of the drying air was not known, and at the bottom the moisture content of the last layer was not known. An iterative solution was obtained by approximating steady state conditions from previous observations and then iterating the results many times until the conditions throughout the bed converged to steady state.

Counterflow simulation of a drying test can be performed only with a fixed bed depth. As with the concurrent flow simulations, the method for finding the zero of unknown functions was used to determine the grainflow rate necessary to dry to the desired final moisture.

Fig. 5 presents typical results of a counterflow simulation. With the counterflow process, it is possible to saturate the drying air and continuously condense moisture from the air onto the incoming cold grain. Condensation occurs whenever the temperature of the exhaust air, as calculated from the sensible heat exchange of the air and the grain, and the latent heat of the water evaporated, falls below the wet-bulb temperature of the drying air. In the counterflow drying zone, the rate of moisture removal is approximately constant. The equilibrium moisture content decreases as the corn moves through the dryer which increases the drying stress on the kernels. A counterflow dryer is very similar to a counterflow heat exchanger. The air and the grain, while traveling in opposite directions, exchange heat energy throughout the whole bed. Depending on the bed depth, the drying air is exhausted at approximately the wet-bulb temperature of the heated air entering the drying column, while the grain is discharged at a temperature only a few degrees below the incoming air temperature.

Summary and Conclusions

The mathematical drying models developed and presented in this paper can be used to predict the performance of crossflow, concurrent flow, and counterflow convection grain dryers with drying temperatures up to 350 F. With the procedures developed and the use of high-speed digital computers, it is possible to study many aspects of convection drying problems that would be difficult if not impossible to obtain in the laboratory or in field applications. The predicted results as determined by these mathematical models permit complete analysis of conventional and newly developed drying methods, and are helpful in the design of drying equipment.

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