Development of a mathematical model for predicting the drying rate of single layers of shelled corn

John Michael Troeger
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Iowa State University of Science and Technology, Ph.D., 1967 Engineering, agricultural

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DEVELOPMENT OF A MATHEMATICAL MODEL FOR PREDICTING
THE DRYING RATE OF SINGLE LAYERS OF SHELLED CORN

by

John Michael Troeger

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
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Approved:

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Dean of Graduate College

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Ames, Iowa

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INTRODUCTION

Historically grain has been preserved by reducing its moisture content to a safe storable level. A low moisture content results in decrease of respiration by the grain and inhibition of activity by microflora in the grain, both of which are sources of deterioration in grain quality.

In the past, most drying has been done in the field before harvest, with nature providing the heat energy and air movement necessary for removing moisture from the grain. With the development of high capacity harvesting machines, and the desire to complete the harvest as quickly as possible to insure against losses due to unfavorable weather, the need for postharvest drying of the grain has become important.

Generally grain is placed in a bulk container, and air is passed through it. As the air moves through the grain, the air temperature drops as it gives up the heat energy used to evaporate the moisture in the grain. At the same time, the humidity of the air increases as the air picks up water that has been evaporated from the grain. If the column of grain is deep enough, the air will reach equilibrium with the moisture in the grain. Beyond this point no further drying can occur.

Within the zone of drying, the rate at which the moisture content of the grain changes is a function of several external variables, such as the dry bulb temperature and relative humidity of the air and the velocity of the air past the kernel. Drying rate also depends on the level and distribution of moisture in the kernel.

Hukill (21) has pointed out that a description of the drying pattern
for fully exposed single layers of grain is useful in describing the changes which occur within the drying zone. In a bin dryer, conditions surrounding the kernel are continuously changing, dictated by the manner in which each preceding layer has dried. An accurate description of changes in a single layer within a batch of grain is difficult to obtain since the sample cannot be weighed periodically without disrupting the system. In a laboratory controlled experiment using single layers of grain, however, conditions can be held constant. Periodic weighings of small fully exposed samples can be readily accomplished. The results can be described in terms of the constant test conditions and applied to a batch of grain by considering each layer as fully exposed to the exhaust conditions of the immediately preceding layer for an infinitesimal time period. An integration procedure would lead to a description of the drying pattern for the entire bin.

In describing the drying conditions of a single layer of grain which is fully exposed to constant surrounding conditions, a number of factors must be considered. Movement of moisture out of the kernel, whether as liquid or vapor, involves a mass transfer mechanism. Heat flow into the kernel to supply the energy required for vaporizing the moisture entails a heat transfer mechanism. These basic phenomena are supplemented by chemical reactions which interact with both moisture and heat flow. In working with grain, a biological aspect must be considered since the kernel is, or once was, a living organism.

Since all of these factors enter into the complex mechanism of drying, accounting for all of them by simply measuring the change in
total weight is, perhaps, an impossibility. However, as better
instruments and controls become available for obtaining data, and as the
basic theories are examined and revised on the basis of better quality
data, the description of the drying mechanism can be improved.
OBJECTIVES

The objectives of this research include the following:

1. To obtain laboratory data which accurately describe the drying patterns of single layers of shelled corn exposed to constant conditions. The variables to be considered include the dry bulb temperature and relative humidity of the air, the air velocity, the initial grain temperature and the initial moisture content of the grain. Tests are to be run until the change in moisture level is negligible.

2. To determine from the data a more accurate concept of the manner in which the different variables affect flow of moisture out of the grain.

3. To select a mathematical model which will satisfactorily describe the manner in which single layers of corn subjected to constant conditions will dry. Coefficients for this model will be examined to determine their dependence on the test variables.
REVIEW OF LITERATURE

A number of researchers have reported attempts to describe, both subjectively and objectively, how various materials dry. In many cases, these models succeed in accurately describing the initial part of the drying curve but fail in describing the final part as the material approaches equilibrium with the surrounding air.

In general, a porous solid saturated with moisture may begin to dry at a constant rate (18) because the material presents, in effect, a free water surface. For grain, however, the constant rate period is seldom encountered because it occurs before the crop is mature enough for harvest. In drying high moisture crops such as sweet corn or freshly-cut hay, however, it might be noted. The constant rate period is followed by a falling rate period during which moisture must be removed from the interior of the material. Study of the falling rate period has been reported in the literature by numerous investigators. Several theories have been advanced to explain the method of moisture removal during this period.

Moisture Concentration Gradient

In searching for a model for describing the drying rate of a porous solid, a common assumption has been that Fick's first law of diffusion (8, 10) is applicable, i.e., that the drying rate is proportional to the moisture concentration gradient within the material. In mathematical terms this is stated:

\[ Q = -D \frac{\partial m}{\partial x} \]  

(1)
where \( Q \) = rate of flow per unit area
\[ D = \text{diffusion coefficient} \]
\[ m = \text{moisture concentration} \]
\[ x = \text{linear distance} \]

This expression, in general, is consistent only for an isotropic medium whose diffusion properties at a point are the same relative to all directions. Equation 1 has been solved theoretically by using a constant coefficient of diffusion, for various regularly shaped objects such as a sphere \((a,24,37)\) and a flat brick \((30)\). Becker \((5)\) employed this equation to describe the drying characteristics of irregularly shaped objects (including wheat), using a surface area-to-volume ratio as the characteristic shape factor. These solutions, when fitted to experimental data, resulted in a satisfactory fit over the initial part of the drying curve. To obtain a better fit of the data Becker \((5)\) assumed a variable diffusion coefficient. He found the diffusion coefficient to be constant over the moisture range of 0.13 to 0.26 gm/gm dry matter but to increase with increasing moisture over the range of 0.076 to 0.13 gm/gm dry matter.

Henderson and Pabis \((16)\) suggested that the failure of the diffusion equation to accurately describe the drying curve during the final stage may be because of an increased energy requirement for desorption at low moisture levels. Becker \((4)\) studied the theoretical relationship between the energy required for desorption and the number of localized sites available within the kernel for adsorption of moisture. He found a correlation between the number of localized sites available and the surface equilibrium moisture content of the kernel. He suggested that
the moisture molecule most closely associated with each localized site was held very strongly and that each subsequent molecule was held at a lower energy level. Dale and Johnson (9) found that the heat required to remove moisture from shelled corn and wheat was up to 1.06 times that of free water for moisture contents above 0.14 gm/gm dry matter but at 0.10 gm/gm dry matter it ranged from 1.15 to 1.20 times that of free water. The higher heat requirement was independent of the temperature or the rate of drying. McEwen et al. (27) suggested that a chemical change takes place within the kernel as it dries, as evidenced by an increase in the specific heat of the kernel at low moisture levels.

According to Gerzhoi and Samochetov (11,p.32) the moisture in grain may be bonded by any of three methods:

a) the chemical bond; water chemically bound to the substance is held most strongly and an especially intensive treatment by heat or chemical action is required for its removal;
b) the physicochemical bond; the adsorbed [strongly held by the substance], the osmotically-absorbed [less firmly held], and the structural moisture [characterized by swelling of the body] belong to this type of bond;
c) the mechanical bond; the capillary moisture [situated in the pores] and the wetting moisture [situated in the pores as well as on the surface] belong to this form.

As drying proceeds, the least tightly bound water is removed first, followed by the more strongly held types. The removal of one form gradually grades into removal of a more closely bound form.

Vapor Pressure Gradient

Babbitt (3) pointed out that the assumption of a moisture concentration gradient as the driving force for the removal of moisture from the kernel, although convenient, is not correct if (as for grain) the moisture
concentration gradient and the vapor pressure gradient are not linearly related. He devised an experiment using a piece of fiberboard, in which the moisture flow was in response to a vapor pressure gradient but against a moisture concentration gradient.

Hukill and Schmidt (22) suggested that the rate of flow at a point in the kernel is a function of the kernel humidity gradient. Kernel humidity was defined as the relative humidity that is in equilibrium with the average moisture content of the kernel at a given time. Since the relative humidity is directly proportional to the vapor pressure for a given temperature, the rate of flow will also be a function of the vapor pressure gradient.

The model of Hukill and Schmidt consists of two aspects describing the change in average moisture content, one for the initial period of drying and the other for the period when the moisture content approaches equilibrium. The rationale for a two-aspect model can be illustrated by considering the drying gradient in an analogous flat plate, which initially has a uniform moisture throughout. As drying begins, a gradient (indicated by the solid lines in Fig. 1) forms and gradually extends toward the center of the plate. Since the gradient is symmetrical about the center, it cannot extend past this point. The upper portion of the gradient then drops more rapidly (indicated by the primed numbers in Fig. 1) extending from the center to join with the original gradient. The dashed lines indicate where the original gradient would fall if it still existed. The average moisture content, represented by the area under the curve, continues to change by the same pattern until the new gradient has
Fig. 1. Hukill-Schmidt flat plate analogy
extended to the surface. After this the pattern describing the change in average moisture content takes a different form, corresponding to the second aspect of the drying curve.

This analogy concerns only the internal resistance to the flow of moisture in the absence of any external resistance. The second term of the model proposed by Hukill and Schmidt accounts for the external resistance to moisture flow. The external resistance is inversely proportional to the square of the kernel humidity gradient. The form of this term remains the same throughout drying.

Variables Affecting Drying

Temperature

Considerable evidence has been accumulated to show that the temperature of the air has an important effect on the drying rate. Simmonds et al. (34) obtained a significantly faster drying rate when the temperature was increased from 70° to 170°F. Other investigators (5,6,22,26) have also reported a significant effect on the diffusion coefficient caused by a change in temperature.

Internal grain temperature is significant in determining internal moisture movement. Becker and Sallans (6) found that the temperature inside a wheat kernel approaches the air temperature very rapidly and except for the first few minutes, the two temperatures are never more than a few degrees apart. Pabis and Henderson (30) showed that the kernel temperature asymptotically approaches the air temperature after drying begins.
Air velocity

An effect of air velocity on drying has been noted by some researchers but not by others. Simmonds et al. (34) reported no significant effect of air velocity on the drying of wheat over a range of 32 to 163 ft per min. Babbitt (1) observed that wheat dries faster in circulated air than in still air. Henderson and Pabis (17) found an effect of velocity at the start of the drying period. They attributed this effect to heat transfer into the kernel rather than vapor removal from the surface. Hukill and Schmidt (22) detected an effect of velocity on the drying rate of grain sorghum when using velocities of 35 to 240 ft per min. Ives et al. (25), using counterflow drying for wheat reported no significant velocity effect. In most cases, the bulk rate of air flow has been used to determine the reported velocity. In actuality the velocity at the kernel surface is the value which affects heat and mass transfer characteristics at the surface but it is more difficult to measure.

Relative humidity

An effect of relative humidity on the first part of the drying pattern has not been observed by all investigators. Simmonds et al. (34) reported a decrease in the rate of drying when the relative humidity of the air increased. They found that a three- to four-fold increase in absolute humidity (gm water/gm dry air) is roughly equivalent to a temperature drop of 50°F. McEwen and O'Callaghan (26) found that the relative humidity has no significant effect on the drying coefficient.

As the grain dries to the state at which it is in equilibrium with the surrounding air, the level of relative humidity and temperature of
the air determine the minimum level to which the moisture may drop. Several researchers have investigated this equilibrium relationship and determined a graphical relationship (13,14,15). Henderson (15) proposed the following mathematical model:

\[ 1 - h = \exp(-c \, T \, m_e^n) \]  

(2)

where \( h \) = relative humidity of the air (decimal form)
\( c, n \) = parameters dependent on the kind of grain
\( T \) = absolute temperature (°R)
\( m_e \) = equilibrium moisture content (percent dry basis)

Hall and Rodriguez-Arias (13) found the parameters \( c \) and \( n \) of Equation 2 to be dependent on temperature. With this modification, Equation 2 agrees with experimental data in the range of 10 to 60 percent relative humidity. At high relative humidities there is a lack of reliable data because of rapid deterioration of the grain under warm, humid conditions.

Size and shape

The size and shape of the material being dried have been considered as significant variables by several investigators. Simmonds et al. (34) observed the drying rate to be inversely proportional to the diameter of the wheat kernel. They found that the diameter of the kernel may change by as much as 15 percent during drying. Becker (5) considered a shape criteria (surface area-to-volume ratio) in applying a theoretical equation to the drying curve of wheat.
Predrying treatment

Another variable to be considered in a study of the drying rate of grain is the treatment of the sample after harvest but before drying. Hustrulid (23) reported no significant difference in the drying rates of corn stored at 0-10°F and at 35-40°F. He did find a difference between naturally moist corn and samples that had been remoistened. Ives et al. (25) reported that wheat stored for 21 days dried 3 percent faster than freshly harvested grain. Henderson and Pabis (16) pointed out the difficulty of obtaining a uniform moisture content in fresh samples. They also noted that stored samples were subject to variations which made them not representative of naturally wet, undried grain.
ACQUISITION OF EXPERIMENTAL DATA

Equipment

A laboratory dryer was designed and constructed for holding single layered samples under constant drying conditions for several weeks. Temperature, relative humidity and air velocity were accurately maintained in the system for the desired exposure time. The system (Fig. 2) consisted of an exposure chamber for holding the samples, a packed tower for saturating the air at the dew point temperature and a heater section for maintaining the desired dry bulb temperature.

The exposure chamber (Fig. 3) consisted of four cells, each having a separate velocity control. Each cell held four samples (Fig. 4), giving a capacity of 16 samples for each test run. The chamber was well insulated, and an additional amount of conditioned air was passed through an open space surrounding the chamber as an aid in maintaining a minimum temperature gradient within the sample chamber.

The samples, weighing approximately 50 grams each, were placed in 4 x 8 inch trays made of screen wire on a metal frame. A screen wire cover was used to prevent accidental spilling during handling.

The drying air was conditioned by first passing it upward through the packed tower (Fig. 5) while water moved down through the ceramic saddle packing material. The water used for saturating the air was maintained at the desired dew point temperature in a water bath beneath the packed tower. Excess water droplets remaining in the saturated air were removed by a furnace filter placed above the packed tower. Close
Fig. 2. Schematic drawing of exposed kernel drying apparatus
Fig. 3. Overall view of drying chamber

Fig. 4. Inside view of drying chamber
Fig. 5. Saturation tower and water bath

Fig. 6. Air heater section
agreement between the temperature of the water bath and the temperature of the air leaving the tower assured saturation of the air. The pipe conducting the air from the saturation tower to the heater was well insulated to minimize possible condensation of water from the saturated air.

Temperature of the water bath was regulated by a relay controlled by a mercury sensor submersed in the water bath. The relay operated a solenoid valve, allowing a coolant to circulate through coils in the water bath. Continuous agitation of the water provided a uniform temperature throughout the water bath. If additional heat was required, electric resistance heaters were used. Although the air was generally recirculated, test conditions with a dew point below 50°F sometimes required the use of supplemental outside air to keep from exceeding the capacity of the cooling system. Fluctuations in the temperature of the outside air, however, allowed less precise control of the dew point temperature by this method.

The saturated air was passed through a bank of electric resistance heaters to raise the temperature of the saturated air to the desired dry bulb temperature. The amount of heat added to the air was controlled by a wire wound resistance type sensor placed at the entrance to the drying chamber. Baffles placed in the air stream thoroughly mixed the air before it reached the sensor. The air then passed upward through the samples and recirculated in the system.

Since the dew point of this drying system could not be set below about 34°F, a second dryer (Fig. 9) was constructed for maintaining
conditions with a lower dew point (-100° to -50°F). This low humidity dryer also contained four chambers, each holding four samples, giving a capacity of 16 samples per test. The air in the dryer was recirculated through a bed of silica gel which removed water from the air. A refrigeration system cooled the air before it passed through the desiccant, thus allowing more efficient use of the desiccant.

Each cell of the low humidity dryer had a separate temperature and velocity control. Temperatures were maintained by electric resistance heaters controlled by mercury plunger relays. Velocities were measured and controlled by adjusting a gate valve to maintain the pressure drop across an orifice plate (Fig. 10).

Outside leaks into the system were encountered in the initial run. This problem was alleviated by maintaining the pressure inside the dryer at a slightly higher pressure than the atmosphere.

Measurements

Weight

Samples were weighed periodically on a Mettler analytical balance (Fig. 7) which had a capacity of 200 grams and a sensitivity of 0.0001 gram. Samples were removed from the dryer and weighed hot so that some error was encountered due to drifting of the scale. An experienced observer, however, could observe the readings so as to minimize the drift error. Early readings from samples exposed to high relative humidities had considerable drift so that weights for the first part of these samples were subject to large error.
Fig. 7. Precision balance and time clock

Fig. 8. Blower
Fig. 9. Low humidity drying chamber

Fig. 10. Air velocity controls - low humidity dryer
Temperature

Temperatures were measured by placing thermocouples at various points in the system and reading them with a null type precision potentiometer. Sensitivity of the potentiometer was 5 microvolts (about 0.25 F degrees). The potentiometer was balanced against a standard cell before each set of readings to minimize drift of the balance point. The ice pot was changed frequently to assure a constant reference temperature. In addition a recording potentiometer was used to monitor various temperatures continuously and record any major disruptions in the condition of the drying air.

Relative humidity

Relative humidity was computed as the ratio of the saturated vapor pressures of the air at the dew point and dry bulb temperatures.

Air velocity

Movement of air into each cell was regulated by maintaining the desired pressure drop across a calibrated, perforated metal sheet with a given size and number of uniformly distributed open holes. In the low humidity dryer, calibrated orifice plates were used to measure air flow.

To obtain a velocity measurement in the vicinity of the kernel, a thermocouple anemometer was used (20). This anemometer was calibrated in a 4-inch diameter pipe. Its use in the exposure cells, with a much larger cross sectional area, however, gave erratic results. This was apparently due to the various directions of air movement in the larger chamber. Better results were obtained when the anemometer was placed a short distance above the samples. Any movement of the kernels, however, as was
inevitable during the weighing process, varied the velocity pattern past the sample.

Moisture content

Moisture contents of the samples were determined at the conclusion of each test using the standard oven method (35). Observed moisture contents among samples subjected to the same conditions sometimes varied by as much as 0.005 gm/gm dry matter. An average of all the samples in a test was used as the final moisture content for each sample.

Procedure

The corn samples were harvested in the fall at a moisture content of about 0.42 gm/gm dry matter (30 percent wet basis). All samples were hand shelled to minimize mechanical damage. The corn was divided into four lots, and three of these lots were subjected to further unheated air drying using laboratory air. They were dried to moisture levels of 0.36, 0.31 and 0.21 gm/gm dry matter. Each lot was placed in a sealed plastic bag and stored in a refrigerator at 35°F. Some attempts were made to obtain samples directly from the field at all moisture levels, but the unpredictability of obtaining the desired moisture level made this practice less useful.

For steady state conditions the dryer was placed into operation several hours before the start of a test. Samples were taken directly from storage, weighed and immediately placed in the dryer. In some tests, the samples were preheated to the dryer temperature in sealed glass jars before drying.
Each test consisted of sixteen samples, four at each velocity. Characteristics of the four samples within each velocity were varied with different tests. Samples were periodically removed from the dryer for weighing, the interval between weighings being increased as the difference in moisture level between readings became less. Tests were generally continued for two weeks unless curtailed earlier because of a failure of the system. A few tests were continued up to four weeks.

Experiments

Tests were conducted to obtain data describing the drying pattern of fully exposed, single layer samples. Corn was used in most of the tests although soybeans and milo were included in later tests. The variables considered and the nominal values of each, were as follows:

- **Dry bulb temperature:** 90°, 125°, 160°F
- **Relative humidity:** 0, 5, 10, 20, 40, 60, 80 percent
- **Air velocity:** 20, 40, 80, 160 ft per min
- **Initial moisture:** 21, 31, 36, 42 percent dry basis
- **Initial grain temperature:** 35°, 70°, 125°, 160°F

Not all combinations of these variables were included because of limitations of time and equipment. Replicates were run on several of the tests. Several samples were dried under test conditions outside of the above ranges. Some were dried at a temperature of 217°F in the low humidity dryer to duplicate oven drying conditions. A few samples were rewetted but no extensive tests were conducted in this area. A total of 496 samples were dried in 31 tests. A complete summary of the conditions
for all of the samples is given in Appendix A. Data for 208 selected corn
samples are given in Appendix B. Tables 1 to 3 give a further breakdown
of the samples by several classifications. Conditions of the drying tests
for soybeans are included here and in Appendix A for the record, but time
limitations did not allow an analysis of the data as was done for the
corn samples. Four samples using milo are included in the above total of
samples dried but are not included in the following tables.

Table 1. Number of samples by temperature and relative humidity

<table>
<thead>
<tr>
<th>Temperature (°F)</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>40</th>
<th>60</th>
<th>80</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Corn</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>125</td>
<td>10</td>
<td>36</td>
<td>24</td>
<td>78</td>
<td>86</td>
<td>8</td>
<td>24</td>
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<td>160</td>
<td>10</td>
<td>24</td>
<td>8</td>
<td>24</td>
<td>16</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>217</td>
<td>10</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Soybeans</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>125</td>
<td>6</td>
<td>12</td>
<td>8</td>
<td>18</td>
<td>12</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>160</td>
<td>6</td>
<td>8</td>
<td>8</td>
<td>8</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>217</td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Table 2. Number of samples by initial grain temperature

<table>
<thead>
<tr>
<th>Temperature (°F)</th>
<th>Corn</th>
<th>Soybeans</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>219</td>
<td>137</td>
<td>356</td>
</tr>
<tr>
<td>70</td>
<td>16</td>
<td>-</td>
<td>16</td>
</tr>
<tr>
<td>125</td>
<td>71</td>
<td>5</td>
<td>76</td>
</tr>
<tr>
<td>160</td>
<td>44</td>
<td>-</td>
<td>44</td>
</tr>
</tbody>
</table>

Table 3. Number of samples by initial moisture

<table>
<thead>
<tr>
<th>Initial moisture % dry basis</th>
<th>Corn</th>
<th>Soybeans</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>-</td>
</tr>
<tr>
<td>21</td>
<td>60</td>
<td>-</td>
</tr>
<tr>
<td>31</td>
<td>28</td>
<td>-</td>
</tr>
<tr>
<td>36</td>
<td>95</td>
<td>60</td>
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<tr>
<td>42</td>
<td>151</td>
<td>66</td>
</tr>
<tr>
<td>55</td>
<td>-</td>
<td>6</td>
</tr>
<tr>
<td>100</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>350</td>
<td>142</td>
</tr>
</tbody>
</table>
QUALITATIVE EVALUATION OF THE DATA

The experimental data were examined qualitatively to ascertain the effects of the variables on the drying pattern. The data were plotted using moisture (m) and rate (dm/dt) coordinates. Use of the rate rather than the time gives an instantaneous evaluation of the drying process rather than a cumulative evaluation. This plot highlights effects near the start of drying but minimizes differences as the moisture content approaches equilibrium. The method used to determine the drying rate at a point is explained in Appendix D.

Moisture Content

The moisture level of the kernel is the primary indicator of change in the kernel. The observed moisture content indicates the average moisture level of the kernel but does not show the moisture distribution pattern within the kernel. The moisture distribution, in some cases, was judged to be the main difference between the drying patterns of two samples which were similar in all other respects.

A close look at the term "moisture content" shows the imprecision associated with this term. The difficulty in defining moisture was pointed out by Oxley (29, p.16):

The concept of water content implies that grain consists of a dry solid material plus a quantity of water which can vary within wide limits down to zero. This concept is sufficiently near the truth for most practical purposes, but as soon as questions of accuracy of determination are raised, it becomes important to recognize how far it is wrong to think of water and dry matter being merely mixed as distinct from combined in the chemical sense.
Water which is imbibed into a colloidal material (such as grain), is usually said to be partly adsorbed. This means that some water is held relatively loosely by capillary forces in the fine interstices of the solid material (absorbed), while the rest is held much more firmly in very thin layers on all surfaces (adsorbed). These processes grade into each other, and it is impossible to draw a sharp line of demarcation between adsorption and absorption.

Since the absolute amount of moisture in a sample cannot be determined, an arbitrary but repeatable standard is used. The primary standard for a number of years has been the oven method (35) in which the sample is dried at a temperature of 217°F and unspecified vapor pressure for 72 hours, the weight loss after this time being called the moisture content. For practical purposes, the sample is assumed to reach a "constant weight" after the specified time. However, a more precise scale shows that the weight continues to drop indefinitely, resulting in negative moisture contents (Fig. 11). The rate of drying also continues to decrease indefinitely. Whether this continual loss of weight is because of loss of moisture or loss of dry matter or both cannot be determined from the data.

Grain Temperature

Temperature plays an important role in determining the drying rate. Temperature of the grain rather than of the air appears to be more significant. It has been reported by other investigators (30), however, that the grain temperature of a fully exposed layer rapidly approaches the air temperature in an asymptotic manner.

To check differences in drying patterns because of different initial grain temperature, some samples were placed into the dryer directly from cold (35°F) storage while others were first heated to the dryer
Fig. 11. Long term oven drying pattern
temperature in sealed jars. Fig. 12 shows that for typical samples the cold one dried faster than the heated one. Since the opposite would be expected if the observed relationship was due entirely to the temperature difference, it was hypothesized that the distribution of the moisture in the grain may have been the cause of the observed results. Although no significant difference was noted in the average initial moisture content of samples subjected to each of the treatments, the heated samples may have had moisture movement within them during the heating period, setting up a gradient. Thus the cold samples with a more uniform moisture distribution would have a faster rate of drying at the start because more moisture would be near the surface.

Cold samples dried under highly humid conditions (greater than 60 percent relative humidity) generally show an increase in weight shortly after being placed in the dryer. When the kernel temperature is below the dew point of the air, condensation occurs at the grain surface. As the kernel is heated the condensate disappears and drying begins.

Air Temperature

Fig. 13 shows the drying pattern exhibited by samples subjected to different temperatures. After being placed in the dryer the samples appear to be adjusting to their new environment as evidenced by the sharp increase in the drying rate immediately after the start of drying for the high temperature samples and the sharp decrease in the drying rate for the low temperature samples. This adjustment might be accounted for by temperature changes or by changes in the moisture distribution pattern in
Fig. 12. Initial grain temperature effect

Fig. 13. Air temperature effect
MOISTURE, GM/GM OF DRY MATTER

31

SAMPLE | INT | TEMP | R.H | IN.M
--------|-----|------|-----|-----
2353300 |     | 35°F |     | 0.354
2353310 |     | 125°F|     | 0.364

DRYING RATE X 10^3 (-DM/DT), GM/GM·MIN.

TEMP=90°F
125°F
162°F
216°F

SAMPLE | TEMP | R.H | IN.M | INT
--------|------|-----|------|-----
1011410 | 90°F | 0.026| 0.452|
2011410 | 125°F| 0.009| 0.455|
3011410 | 162°F| 0.004| 0.455|
4011410 | 216°F| 0.001| 0.468|

35°F

DRYING RATE X 10^3 (-DM/DT), GM/GM·MIN.
the kernel. All of the samples plotted in Fig. 13 were subjected to air with a low dew point eliminating condensation (mentioned above) as a probable explanation for the observed behavior.

After the adjustment period, the drying patterns exhibit a continually decreasing drying rate with the samples at higher temperatures drying at faster rates. Higher temperatures contribute to higher vapor pressures in the kernels, thus producing more favorable drying gradients. In addition the heat of vaporization of water decreases with higher temperatures, thereby lowering the amount of heat energy needed to vaporize the moisture.

Relative Humidity

Relative humidity shows an influence on the rate throughout the drying process. As the relative humidity decreases (holding temperature constant), the vapor pressure gradient becomes more favorable for moisture movement out of the kernel. The external vapor pressure and the temperature determine the equilibrium moisture content, the limit below which no more moisture can be removed from the kernel. As the moisture content approaches the equilibrium level, the drying rate becomes negligible (Fig. 14).

Relative humidity also influences the initial drying rate (Fig. 15). The initial drying rates used in this plot were estimated by excluding the initial adjustment period mentioned in the preceding section. The procedure for obtaining this apparent initial drying rate is given in Appendix D.
Fig. 14. Relative humidity effect approaching equilibrium

Fig. 15. Relative humidity effect on initial drying rate
DRYING RATE $\times 10^5 (-DM/DT)$, GM/GM-MIN.

SAMPLE | R.H. | TEMP |
---|---|---|
2104410 | 0.05 | 125°F |
2204410 | 0.10 |
2304410 | 0.19 |
2414410 | 0.40 |
2514410 | 0.58 |
2504410 | 0.84 |

DRIED BULB TEMP = 125°F
AIR VELOCITY = 160 fpm
IN. MOIST = 0.42 gm/gm
IN. GRAIN TEMP = 35°F
Air Velocity

Velocity of the air has a significant effect on the first part of the drying curve (Fig. 16). Higher velocities produce faster drying rates. During the initial adjustment period, the lower air velocities exhibit a period of increasing rate before following the expected decreasing rate pattern. This indicates that the initial warm-up period is not as rapid for samples subjected to a lower velocity.

In a large mass of grain, the air flow rate has a noticeable effect on the drying rate because the air acts as the agent for supplying heat to evaporate moisture in the grain and for removing the evaporated moisture from the grain mass. In the single layer drying situation, however, the volume of air flow compared to the grain mass is so large that any changes in the condition of the air as it passes through the grain are negligible. The observed velocity effect was attributed to the change in vapor and heat conductance characteristics outward from the kernel surface. This being external to the kernel indicates that the external resistance to moisture flow has a significant effect on the rate of drying during the early part of a test.

Initial Moisture Content

The effect of initial moisture persists during the first portion of the drying curve, but the difference between the drying rates of samples with different initial moistures becomes indiscernible as the moisture level approaches equilibrium (Fig. 17). The data plotted in Fig. 17 are typical of a large number of the tests, in which the samples with initial
Fig. 16. Air velocity effect

Fig. 17. Initial moisture effect
moisture contents in the range of 0.35 to 0.37 gm/gm dry matter, started
drying at a faster rate than did samples with higher or lower initial
moisture contents.

Speculation on the reason for the observed initial moisture effect
centered on the prestorage treatment of the samples. The highest moisture
samples (0.42 gm/gm dry matter) were stored in a sealed container immedi­
ately after harvest. The remaining samples, however, were dried with
unheated room air to the desired moisture level before being placed in
storage. Prestorage laboratory drying of the samples, being faster than
the preharvest drying, may have changed the internal structure of the
kernel to allow more rapid drying when the samples were subjected to the
test conditions. No data for samples taken directly from the field with
comparable moisture contents were available for testing this hypothesis.

Summary

The qualitative analysis shows that the first part of the drying
curve is an adjustment period in which the kernel drying pattern is trans­
formed to the pattern dictated by the test conditions. From these
observations it was concluded that use of the initial moisture and
temperature of the kernel as the only measures of its predrying condition
do not adequately describe the situation. Knowledge of the distribution
of the moisture in the kernel at the start of drying is also necessary
for describing how it dries during the adjustment period. Distribution
of the moisture was not measured in the present tests.

An effect of air velocity on the drying pattern is clearly evident
during the first part of the drying curve. Relative humidity effects are noted throughout the drying curve at all moisture levels. A temperature effect is also noted at all levels of moisture.
DEVELOPMENT OF A MATHEMATICAL MODEL

Drying is a complex phenomenon which might be considered as a coupled flow process involving several basic mechanisms, each acting simultaneously with several others. Each of these basic mechanisms is influenced to some extent by each of the other mechanisms. Vapor diffuses out of the kernel in response to a vapor pressure gradient while heat flows into the kernel in response to a temperature gradient. At the same time the drying process may be influenced by certain chemical and biological processes which up to the present time have not been described well enough to allow an evaluation of their effects.

Several attempts have been made to describe the drying process in terms of a diffusion mechanism (6,26,37). The mathematical form of such a model for one-dimensional flow with a constant coefficient of diffusion is based on Fick's second law of diffusion (8,p.3) given by:

\[ \frac{\partial m}{\partial t} = D \left( \frac{\partial^2 m}{\partial x^2} \right) \]  

where

- \( m = \) moisture concentration
- \( t = \) time
- \( D = \) diffusion coefficient
- \( x = \) linear distance

This approach assumes that the rate of moisture movement at a point in a homogeneous solid is proportional to the moisture concentration gradient at that point. Generally the object is assumed to be regularly shaped (such as sphere or flat brick). Obviously corn and other grains are neither regularly shaped nor homogeneous in their composition.
so that close quantitative results cannot be expected using this model.

This model does not account for the simultaneous flow of heat into the kernel as moisture is removed. At the beginning of drying the difference between the kernel temperature and the air temperature is greatest. As drying proceeds, the kernel temperature approaches the air temperature asymptotically. Thus at the beginning of drying sensible heat is needed to raise the temperature of the grain in addition to the latent heat needed to vaporize the moisture. The sensible heat term becomes negligible after the warm-up period.

Several researchers (16,24) have applied the relationship:

\[ \frac{dm}{dt} = -k(m-m_e)^a \]  

where 

- \( m \) = average moisture content (dry basis) 
- \( t \) = time 
- \( a \) = arbitrary exponent 
- \( k \) = diffusion coefficient 
- \( m_e \) = equilibrium moisture content

When \( a = 1 \) this equation can be integrated to give:

\[ m-m_e = c e^{-kt} \]  

with \( c \) being a constant of integration. This model appears as a straight line when plotted on semilogarithmic coordinates. Such a plot (Fig. 18) shows that the model approximates the experimental data for only the first portion of the drying curve and consistently underestimates the drying time as the moisture content approaches equilibrium. Satisfaction
Fig. 18. Plot of equation: $m - m_e = c e^{-kt}$
with this model by previous researchers might be explained by the fact that published experimental data rarely include observations taken after the first 24 hours of drying.

Hukill and Schmidt (22) suggested that a better fit of the data could be obtained if the arbitrary exponent in Equation 4 was equal to two. This suggestion was evaluated by plotting experimental data on coordinates of log(dm/dt) versus log(m-m_e). This plot (Fig. 19) indicates that a power of 2.2 is more appropriate than a power of 1.0 but that no single power is best for all portions of the drying curve. The poor fit of the model plotted in Fig. 18 becomes apparent when its differentiated form (Equation 4 with a = 1) is plotted in Fig. 19. The differential form of the model illustrates features of the curve which are smoothed out in the integrated form.
Fig. 19. Plot of equation: \( \frac{dm}{dt} = -k(m-m_e)^a \)
Babbitt (3) showed that moisture diffuses through a porous material in response to a vapor pressure gradient rather than a moisture concentration gradient. This concept was used by Hukill and Schmidt (22) to develop a mathematical model which satisfactorily describes the single layer drying curve for grain sorghum. In this model the kernel humidity is the independent variable. Kernel humidity is defined as the relative humidity in equilibrium with the average moisture content, as indicated by the moisture-relative humidity equilibrium relationship. Since relative humidity is directly related to vapor pressure for a given temperature, this model, in effect, considers a vapor pressure gradient as the potential for drying.

The general mathematical formulation of this model is given as:

\[ t = C_1 \int_{m_o}^{m} \left[ \frac{1}{(h-h_e)} \right] \, dm + C_2 \int_{h_o}^{h} \left( h_o - h \right) \, dm \]

\[ h_o \geq h \geq h_x \]  \hspace{1cm} (6a)

\[ t = C_1 \int_{m_x}^{m} \left[ \frac{1}{(h-h_e)} \right] \, dm + C_3 \int_{h_x}^{h} \left[ \frac{1}{(h-h_e)} \right]^c \, dm + t_x \]

\[ h_x \geq h \geq h_e \]  \hspace{1cm} (6b)

where \( t = \) time

\( m = \) average moisture content (dry basis)

\( h = \) kernel humidity
\( C_1 = \) coefficient of external resistance

\( C_2 = \) coefficient of internal resistance, 1st aspect

\( C_3 = \) coefficient of internal resistance, 2nd aspect

\( a = 2 = \) exponent of external resistance

\( b = 1 = \) exponent of internal resistance, 1st aspect

\( c = 2 = \) exponent of internal resistance, 2nd aspect

Subscripts: \( o = \) initial condition

\( x = \) transition between aspects

\( e = \) equilibrium condition

For this model it is assumed that the moisture content is initially uniform throughout the kernel. Internal and external resistances to moisture flow out of the kernel are assumed to act independently of one another.

Evaluation of the Hukill-Schmidt Model

The integral terms in Equations 6a and 6b were evaluated by numerical methods (Appendix C) using the moisture-relative humidity relationship shown in Fig. 20. These curves are based on the equilibrium moistures indicated by the single layer drying data and by similar data in the literature (13,15). The equilibrium moisture content for a given sample was determined by extrapolating the square root of the drying rate to determine the moisture content at zero drying rate. Evaluation of the integrals was done on a high-speed digital computer (IBM 360/50). Use of the computer saved considerable time compared to hand methods and allowed a large amount of data to be examined.
Fig. 20. Moisture-relative humidity equilibrium curves
Coefficients were estimated using the method of least squares in which the squared deviations of time were minimized. The least squares method implies several assumptions (28,p.126): 1) the independent variable (moisture) is measured without error, 2) for a given value of the independent variable, the possible values of the dependent variable (time) are independently and normally distributed, 3) the variance of the dependent variable associated with a particular value of the independent variable is the same for all values of the dependent variable. These assumptions were not completely satisfied so that erroneous estimates were obtained for the coefficients for a few of the samples. The method was, however, applied to most of the samples with satisfactory results.

Coefficients were computed separately for each aspect with the transition between the two aspects given by:

\[ h_x = \left[ \frac{c}{b+c} \right] (h_o-h_e) + h_e \]  

(7)

Assumptions used in obtaining this relationship are given in Appendix C.

The model was first evaluated with the fixed values of the exponents used by Hukill and Schmidt \( (a=2, b=1, c=2) \). A better fit of the data was obtained, however, when the exponents \( b \) and \( c \) were arbitrarily set. Arbitrary exponents were obtained for 160 samples covering a wide range of conditions. Study of the exponents picked in this manner showed that \( b \) is a function of the dry bulb temperature and initial moisture content while \( c \) is a function of dry bulb temperature and relative humidity.

Empirical equations developed for these exponents are as follows:
\[ b = 1.405 + 0.00220T - 1.283 m_o \tag{8a} \]
\[ c = 2.315 - 0.00123T - 0.111 h_e \tag{8b} \]

where \( T \) = dry bulb temperature (°F)
\( m_o \) = initial moisture (gm/gm dry matter)
\( h_e \) = relative humidity (decimal form)

For the samples used in evaluating these exponents (see Appendix B), \( b \) ranged from 1.0 to 1.5 and \( c \) ranged from 2.07 to 2.18.

The integrals were evaluated using computed values for the exponents. Coefficients were then estimated by the method of least squares, minimizing the squared deviations of time. Examination of the resulting coefficients led to the following empirical relationships for prediction:

\[ C_1 = 2505 - 0.937 V - 512 h_e - 3303 m_o - 1639 m_o^2 \]
\[ - 66.5 m_o T + 144.2 m_o^2 T \tag{9a} \]

\[ C_2 = -6049 + 786 T - 72,400 h_e^2 + 179,000 m_o \]
\[ + 1018 T h_e^2 - 2718 T m_o \tag{9b} \]

\[ C_3 = -200 + 3.79 T - 1044 \log_e (h_e + 0.01) \tag{9c} \]

where \( V \) = air velocity (ft per min)

Plots of typical samples are shown in Figs. 23 through 28.
Discussion of Results

After defining the coefficients and exponents in terms of the empirical equations given above, the Hukill-Schmidt model was found to give a satisfactory representation of most of the experimental data. It is not possible, however, to account for extreme variations in the drying pattern, particularly during the warm-up period. This is most often noted in samples subjected to conditions with a low drying potential. The study shows that a two-aspect model is definitely superior to the single-aspect models that have been proposed in the past.

The close agreement of this model with the experimental data indicates that the use of the kernel humidity concept as the means for introducing the vapor pressure gradient into the drying equation is a valid approach. Some difficulty was encountered in defining the moisture-relative humidity equilibrium curve at high moistures. Reliable data are difficult to obtain because the samples deteriorate rapidly under these conditions. The equilibrium curve was established by extrapolation at the high moistures. There is always a question of whether failure of the model to describe a particular set of data is because of the model, the equilibrium relationship or an irregularity of the data caused by a change in the drying conditions.

In describing the coefficients and exponents, the air velocity is included in the equation. The value used for the velocity is a nominal value based on the total air flow rate through the cell rather than a velocity in the vicinity of the kernel. Initial temperature of the grain is not used in the empirical equations because an adequate number of
levels of this variable were not included in the tests to determine its effect quantitatively.

The lengthy procedure used in evaluating the integrals for this model makes evaluation by hand methods extremely tedious. The high-speed digital computer used in this analysis made it possible to evaluate the integrals rapidly so that a large number of samples could be examined in obtaining the empirical equations for predicting the coefficients and exponents. These equations were developed after considerable search through various combinations of the test variables. They give a satisfactory representation of the experimental data over the ranges of the variables used in the tests but could, with continued effort, be improved.
DEVELOPMENT OF THE THREE-ASPECT EXPONENTIAL MODEL

The plot of the moisture gradient \((m-m_e)\) versus the drying rate \((dm/dt)\) on logarithmic coordinates (Fig. 19) suggests that the drying curve can be satisfactorily represented by a three-aspect model, each aspect approximating a straight line on this plot. To facilitate analysis, the data were reduced to dimensionless form using the coordinates of moisture ratio \(m_r\):\
\[
\frac{(m-m_e)}{(m_0-m_e)}
\]
and rate ratio \(r_r\):\
\[
\frac{(dm/dt)}{(dm/dt)} \bigg|_{m_r = 0.2}
\]
The base rate at \(m_r = 0.2\) was chosen because this point always appears in the relatively stable second aspect. Representative data showing the initial moisture and relative humidity effects on the drying data are plotted in Figs. 21 and 22.

Characteristics of the first aspect are influenced to a great extent by the initial and predrying conditions. During the warm-up period (30 to 60 min) the data exhibit departures from the proposed model. The second aspect, however, is relatively stable. Its slope appears to depend only on the relative humidity. Characteristics of the third aspect are difficult to ascertain because of insufficient or erratic data during this portion of the drying curve.

The model is described in the following mathematical form:
Fig. 21. Initial moisture effect - dimensionless log plot
Fig. 22. Relative humidity effect - dimensionless log plot
\[
\frac{dm}{dt} = -a_1 (m-m_e) \quad m_o \geq m \geq m_{x1} 
\]
\[
\frac{dm}{dt} = -a_2 (m-m_e) \quad m_{x1} \geq m \geq m_{x2} 
\]
\[
\frac{dm}{dt} = -a_3 (m-m_e) \quad m_{x2} \geq m \geq m_e 
\]

where \(a, b = \) arbitrary parameters

\(m_o = \) initial moisture (gm/gm dry matter)

\(m_{x1}, m_{x2} = \) transition moistures

\(m_e = \) equilibrium moisture

\(t = \) time (min)

To obtain equations for predicting the time associated with a given moisture level, the following initial and boundary conditions are imposed:

1) at \(t = 0, m = m_o\)

2) at the transition points, time is continuous

3) at the transition points, the drying rate \(\left(\frac{dm}{dt}\right)\) is continuous.

The integrated equations for \(b \neq 1\) are:

\[
t = p_1 (m-m_e)^{q_1} - p_1 (m_o-m_e)^{q_1} \quad m_o \geq m \geq m_{x1} 
\]
\[
t = p_2 (m-m_e)^{q_2} - p_2 (m_{x1}-m_e)^{q_2} + t_{x1} \quad m_{x1} \geq m \geq m_{x2} 
\]
\[
t = p_3 (m-m_e)^{q_3} - p_3 (m_{x2}-m_e)^{q_3} + t_{x2} \quad m_{x2} \geq m \geq m_e 
\]

where \(p = -\frac{1}{a(1-b)}\)

\(q = 1 - b\)

The times at the transition points are:
By the third boundary condition listed above, i.e., that the drying rate is continuous through the transition region, the points of transition are given by:

\[ m_{x1} = \left( \frac{p_1 q_1}{p_2 q_2} \right)^{1/(q_2-q_1)} + m_e \]  \hspace{1cm} (12c)

\[ m_{x2} = \left( \frac{p_2 q_2}{p_3 q_3} \right)^{1/(q_3-q_2)} + m_e \]  \hspace{1cm} (12d)

Evaluation of the Exponential Model

Essential for use of the exponential model is a knowledge of the equilibrium moisture associated with a given set of test conditions. The equilibrium moisture for each sample was estimated by extrapolating the square root of the drying rate to obtain the moisture content when the drying rate is zero. In most cases this value compares favorably with a similar value obtained from the equilibrium curve.

To evaluate the coefficients and exponents in terms of the experimental data, it was necessary to arbitrarily set the transition points to bound the region over which each aspect would be fitted. The following values were used:

\[ m_{x1} = 0.40 (m_0 - m_e) + m_e \]  \hspace{1cm} (13a)

\[ m_{x2} = 0.12 (m_0 - m_e) + m_e \]  \hspace{1cm} (13b)
These points were selected after studying samples subjected to a wide variety of conditions.

The exponents were first estimated by fitting the logarithmic forms of Equations 10a, 10b and 10c:

\[
\log (-\frac{dm}{dt}) = \log a + b \log (m-m_e) \quad (14)
\]

to the experimental data by the method of least squares, by minimizing the squared deviations of \(\log (-\frac{dm}{dt})\). These results were examined to determine if the exponents could be predicted as functions of the test variables. After considering a number of combinations of the test variables, the following empirical equations were selected:

\[
q_1 = -3.98 + 2.87 m_o - \left[ \frac{0.019}{(h_e+0.015)} \right] + 0.016 T \quad (15a)
\]

\[
q_2 = - \exp (0.810 - 3.11 h_e) \quad (15b)
\]

\[
q_3 = -1.0 \quad (15c)
\]

where \(h_e\) = relative humidity (decimal form)

\(T\) = dry bulb temperature (°F)

Using the exponents computed by the above equations, Equations 11a, 11b and 11c were fitted to the experimental data by the method of least squares, by minimizing the squared time deviations. The coefficients obtained by this procedure were examined to determine their dependence on the test variables. The following empirical equations were developed to predict coefficients \(p_1\) and \(p_2\):
\[ p_1 = \exp(-2.45 + 6.42 m + 1.25 m^0 - 3.15 h + 9.62 m^0 \sqrt{h}) \]
\[ + 0.030 T - 0.002 V) \]  
\[ p_2 = \exp (2.82 + 7.49(h_e + 0.01)^{0.67} - 0.0179 T) \]  
(16a)

where \( V = \) air velocity (ft per min)

It should be noted that if both \( p_1 \) and \( p_2 \) are defined empirically, then the definitions of \( m_x \) given by Equations 12c and 13a cannot both, in general, be satisfied. It was noted that a better fit of the data could be obtained if both \( p_1 \) and \( p_2 \) were defined empirically. So if Equation 13a is satisfied, then Equation 12c will not be satisfied, thus negating the assumption of a continuous drying rate through the first transition point. Further refinement of Equations 16a or 16b might allow this assumption to be made.

Because of the lack of good quality data for several of the samples in the region below the second transition point, coefficient \( p_3 \) was defined in terms of Equations 12d and 13b, thus satisfying the assumption of a continuous rate of drying at the second transition point.

\[ p_3 = 0.12 (m - m^0) (q_2 - q_3) (p_2 q_2 / q_3) \]  
(16c)

Plots of the predicted drying curve for several samples covering a wide range of conditions are given in Figs. 23 through 28.
Fig. 23. Comparison of models - Sample 1314410

Fig. 24. Comparison of models - Sample 1502310
SAMPLE 1314410
TEMP. 92°F
R.H. 0.192
IN. M 0.430
VEL 160fpm

○ EXPERIMENTAL DATA
- 3-ASPECT MODEL
- HUKILL-SCHMIDT MODEL

SAMPLE 1502310
TEMP. 90°F
R.H. 0.587
IN. M 0.360
VEL 40fpm

○ EXPERIMENTAL DATA
- 3-ASPECT MODEL
- HUKILL-SCHMIDT MODEL
Fig. 25. Comparison of models - Sample 2104110

Fig. 26. Comparison of models - Sample 2301310
SAMPLE 2104110
TEMP 122°F
R.H. 0.048
IN.M 0.214
VEL. 160fpm

SAMPLE 2301310
TEMP 126°F
R.H. 0.189
IN.M 0.360
VEL 20fpm

O EXPERIMENTAL DATA
--- 3 ASPECT MODEL
--- HUKILL-SCHMIDT MODEL

MOISTURE, GM/GM DRY MATTER

TIME, HRS.
Fig. 27. Comparison of models - Sample 2304410

Fig. 28. Comparison of models - Sample 3121410
Discussion of Results

The three-aspect exponential model with computed coefficients and exponents gives a satisfactory fit of the experimental data throughout the drying curve. As was true of the Hukill-Schmidt model, irregularities in the data, particularly during the warm-up period, cannot be accurately predicted.

An examination of the model shows one possible source of invalidity. The empirical equation describing exponent $q_1$ (Equation 15a) allows the value of $q_1$ to become zero under certain conditions. If $q_1$ is equal to zero then $b_1$ in Equation 10a is equal to one. For this special case, integration of Equation 10a gives:

$$t = \frac{-1}{a_1} \left[ \log(m_m) - \log(m_e) \right]$$

or

$$m_m = (m_m e^{a_1 t})$$

which is similar to Equation 5 discussed in a previous section. It is of interest to determine under what conditions Equation 15a would yield a value of $q_1 = 0$. The results are given in Table 4. Obviously the conditions of high temperature and high relative humidity required to obtain a zero or positive value for $q_1$ will not be encountered under most conditions. It should be noted that the empirical equations describing $q_2$ and $q_3$ do not allow non-negative values for these exponents.

This model assumes that the drying curve can be represented as a function of the moisture gradient $(m_m)$ raised to some power.
Comparison with the Hukill-Schmidt model based on a vapor pressure gradient shows no superiority of one over the other in their ability to predict the drying curve. Comparison with previous models based on a moisture concentration gradient shows a definite advantage for the present model, using a moisture gradient with a power other than unity for describing the drying curve.

The exponential model is relatively easy to apply, even by hand methods. Consider the following example:

What is the time required to dry a single layer of fully exposed shelled corn from 30 percent to 14 percent wet basis (42.8 to 16.3 percent dry basis) under the following conditions:

Dry bulb temperature of the air = 90°F;

<table>
<thead>
<tr>
<th>$q_1$</th>
<th>$m_o$</th>
<th>$h_e$</th>
<th>$T$</th>
</tr>
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<td>(gm/gm)</td>
<td>(decimal)</td>
<td>(^F)</td>
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<td>90</td>
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<td>0</td>
<td>90</td>
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<tr>
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<td>0.20</td>
<td>0.85</td>
<td>90</td>
</tr>
<tr>
<td>-1.42</td>
<td>0.45</td>
<td>0.85</td>
<td>90</td>
</tr>
<tr>
<td>-1.14</td>
<td>0.20</td>
<td>0</td>
<td>220</td>
</tr>
<tr>
<td>-0.44</td>
<td>0.45</td>
<td>0</td>
<td>220</td>
</tr>
<tr>
<td>+0.11</td>
<td>0.20</td>
<td>0.85</td>
<td>220</td>
</tr>
<tr>
<td>+0.67</td>
<td>0.45</td>
<td>0.85</td>
<td>220</td>
</tr>
</tbody>
</table>
Relative humidity = 20 percent; 
Air velocity = 160 ft per min.

From the equilibrium curve (Fig. 20) the equilibrium moisture content is 6.80 percent (dry basis). The moisture differences are:

\[ m_0 - m_e = 0.428 - 0.068 = 0.360 \]
\[ m_{x1} - m_e = 0.40 (0.360) = 0.144 \]
\[ m - m_e = 0.163 - 0.068 = 0.095 \]

The coefficients and exponents (Equations 15a, 15b, 16a, 16b) are:

\[ p_1 = \exp(-2.45 + (6.42)(0.428)^{1.25} - (3.15)(0.20) + (9.62)(0.428)(\sqrt{0.20}) + (0.030)(90) - (0.002)(160)) = 28.8 \]
\[ p_2 = \exp(2.82 + (7.49)(0.21)^{0.67} - (0.0179)(90)) = 46.5 \]
\[ q_1 = -3.98 + (2.87)(0.428) - (0.019)/(0.215) + (0.016)(90) = -1.40 \]
\[ q_2 = -\exp(0.810 - (3.11)(0.20)) = -1.207 \]

The first transition time is given by Equation 12a:

\[ t_{x1} = (28.8)(0.144)^{-1.40} - (28.8)(0.360)^{-1.40} = 311 \text{ min} \]

The desired time is predicted by Equation 11b:

\[ t = (46.5)(0.095)^{-1.207} - (46.5)(0.212)^{-1.207} + 311 = 809 \text{ min} \]
or 13.5 hr

The input conditions used in this example are similar to Sample 1314410 which is plotted in Fig. 23.
APPLICATION OF RESULTS TO DEEP LAYER DRYING

How can the results of this study be applied to the practical problem of describing the drying pattern in a bin of grain? The first layer is, of course, fully exposed to the entering air conditions and so will dry according to the single layer model. Each succeeding layer, however, is exposed to conditions which are continuously changing depending on the response of all preceding layers. The change in humidity of the air as it passes through a given layer of grain can be estimated by writing a mass balance for that layer. Any moisture lost by the grain must be picked up by the air. The change in temperature of the air as it passes through a given layer of grain can be estimated by writing an energy balance for that layer. If it is assumed that there is no heat lost through the sides of the bin, then the heat given up by the air must be equal to the sensible heat required to raise the temperature of the grain plus the latent heat required to evaporate the moisture leaving the grain. The heat needed to raise the temperature of the grain is generally small relative to the heat used to evaporate the moisture and so it might reasonably be neglected to simplify the computations.

The remaining link needed to make this approach feasible is a method for describing the manner in which moisture leaves the grain under the conditions prevailing in a bin. The single layer model has been developed from the drying data of samples which were subjected to constant drying conditions. For continually changing conditions a first approximation might be made by the direct application of the single layer model for the conditions prevailing at a given point and time in the bin. In
actuality, however, the grain must go through an adjustment period before it will follow the single layer model corresponding to the conditions at that point and time. If the increments of depth and time can be chosen small enough, then the condition of the air will change by only a slight amount as it passes through each layer. Thus the single layer model might be used, but with a time lag to allow for continual adjustment of the grain to the new conditions. The validity of such an approach awaits actual trial.

With the availability of high-speed digital computers, the above approach could be programmed in a stepwise manner to simulate drying in a bin. The results from each layer and time would depend on all preceding layers and times. The ability to simulate deep bed drying would be useful in the future design of more efficient drying systems.
SUMMARY AND CONCLUSIONS

Experimental data describing the single layer drying curve for shelled corn were obtained in the laboratory under constant controlled conditions. The variables considered include the dry bulb temperature of the air (90° to 160°F), the relative humidity of the air (0 to 80 percent), the velocity of the air (20 to 160 ft per min), the initial moisture content of the grain (21 to 42 percent dry basis) and the initial temperature of the grain (35 to 160°F). The samples, most of which remained in the dryer for about two weeks, show a continual decrease in weight, never attaining a condition of constant weight.

Two mathematical models were evaluated in terms of the laboratory results to determine their ability to describe the data. The first model, proposed by Hukill and Schmidt (22), involves the concept of a vapor pressure gradient as the primary drying potential. The coefficients and exponents for this model are described in terms of the test variables and a satisfactory fit of the experimental data results.

The second model was developed from observation of the data. It consists of three aspects, each of the form:

$$\frac{dm}{dt} = a (m-m_e)^b$$

The coefficients and exponents of this model are also described in terms of the test variables and give a satisfactory fit of the experimental data. Comparison of the two models shows no superiority of one over the other in their ability to fit the data. Since the degree to which the empirical equations defining the coefficients and exponents are refined
is not necessarily the same, an attempt to compare the two models in a quantitative manner was not attempted.

Neither of the models is successful in accurately describing the initial warm-up period. During this period the data indicate that the samples are undergoing an adjustment period from their predrying conditions to the drying pattern dictated by conditions to which they were subjected in the dryer. It was hypothesized that the predrying conditions are determined not only by the sample's initial moisture content and temperature but also by its internal moisture distribution. In addition, its structure is probably altered by biological and chemical processes during the period of storage.

A qualitative evaluation of the data reveals that higher temperatures effect faster drying rates at all levels of moisture. Likewise, higher air velocities also cause faster drying rates, but only during the first part of the drying curve. An increase in relative humidity decreases the rate of drying at all moisture levels. Higher initial moistures, in general, produce faster drying rates but some discrepancies, attributed to the manner in which the samples were prepared before storage, were noted. Higher initial grain temperatures produced lower drying rates. This unexpected result was attributed to the method in which the heated samples were prepared before drying.
SUGGESTIONS FOR FUTURE STUDY

Some suggestions for future studies of single layer drying include the following:

1. The initial temperature of the grain should be examined in greater detail than was possible in this study.

2. A systematic study of the effect of the length of storage on the drying curve should be attempted. Both the first and second suggestion involve a method for defining the initial moisture gradient in the kernel.

3. Examination of the effect of initial moisture contents below the range included in this study would be beneficial in extending the range of validity of the models. Also the ability of these models to predict the rewetting curve might be studied.

4. A technique for precise measurement of the air velocity past the kernel would aid greatly in defining the effects of this variable.

5. Obtaining exposed kernel drying data for other grains would establish whether these models are applicable (with different coefficients and exponents) for predicting the drying curve of those grains.

6. Development of a program using the single layer model as well as the heat and mass balance equations, for simulating the drying pattern in a deep bed dryer would establish the practical application of the single layer drying model.
REFERENCES


ACKNOWLEDGEMENTS

The author wishes to express his sincere appreciation to Professor William V. Hukill for his guidance and counsel during the course of this study. Professor Hukill's ability to ask the pertinent question when progress appears to be stopped is a continual source of amazement.

The author would like to thank Messrs. Robert Saul, James Steele and Vergil Haynes for their helpful suggestions and assistance during the various phases of the project, from construction of the dryer and conducting the tests to the interpretation and analysis of the results.

Special thanks is extended to the members of the author's committee, Drs. C. W. Bockhop and T. E. Hazen of the agricultural engineering department, Professor H. M. Black of the mechanical engineering department and Dr. F. G. Smith of the department of botany and plant pathology.

Sincere appreciation is also expressed to other members of the agricultural engineering staff at Iowa State University for their guidance and suggestions.

Gratitude is expressed to the U.S.D.A. for support in providing funds and facilities for conducting this study.

Last, but certainly not least, the author would like to express his sincere thanks to his parents, Mr. and Mrs. Walter Troeger for their continued guidance and support in this endeavor.
APPENDIX A: SUMMARY OF LABORATORY EXPERIMENTS

Fig. 29 gives a complete summary of the conditions under which each sample was dried. Data for corn, soybeans and milo are included in this summary. Sample numbers are coded (with a few exceptions) in the following manner:

1st digit - dry bulb temperature level
2nd digit - relative humidity level
3rd digit - replication
4th digit - air velocity level
5th digit - initial moisture level
6th digit - duplicate of above digits in one test
7th digit - kind of grain.

The first three digits are common for a given test except for samples dried in the low humidity dryer where several temperatures were used in the same test.

A test normally consisted of 16 samples dried at four initial moisture levels and four air velocity levels. When both corn and soybeans were included, only two levels of initial moisture were used. Following are comments on several tests in which the normal procedure outlined above was not used.

Test 231 - All samples had the same initial moisture. Half of the samples were preheated before drying and half were taken directly from storage.

Test 232 - Four samples were corn which had been stored. The remaining samples were from freshly harvested ears with corn from a single ear
 retaining its identity during drying.

Test 233 - Four of the samples had initial moistures below the normal range. Four samples were rewetted after having been oven dried. The remaining eight samples were harvested during two different seasons.

Test 234 - Half of the samples were soybeans. The other half of the samples were corn, harvested during two different seasons.

Test 235 - Six samples of corn, six samples of soybeans and four samples of milo were dried. Half of the samples were preheated before drying while the other half were taken directly from storage.

Fig. 29 summarizes the following variables:

TEMP - dry bulb temperature, deg F.
R.H. - relative humidity, decimal form.
IN,M - initial moisture, gm/gm dry matter.
EQ,M - equilibrium moisture, gm/gm dry matter.
IN.RATE<sup>a</sup> - initial rate of drying, gm/gm min.
VEL - air velocity, ft per min.
IN,T - initial grain temperature, deg F.
STOR - storage time, days.
YEAR - year of harvest.
DATE - date laboratory test began.

<sup>a</sup>The initial rate recorded in the summary is the apparent initial rate. The procedure for determining the apparent initial drying rate is given in Appendix D. The notation for the initial rate is interpreted as: 
-1.193 E - 03 = -1.193 x 10<sup>-3</sup>. 
<table>
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<th>IN.M</th>
<th>EQ.M</th>
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<th>VEL</th>
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Fig. 29. Continued
APPENDIX B: SELECTED SAMPLE DATA

On the following pages are the experimental data for selected samples of corn. The data in Fig. 30 are for the 160 samples used in evaluating the two mathematical models described in this report. Fig. 31 gives additional data which were used in the qualitative evaluation of the results. Test conditions for all of the tests are given in Appendix A. The dimensions of the variables are: time, min and moisture, gm/gm dry matter.
**Fig. 30. Continued**
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Fig. 31. Other selected experimental data
APPENDIX C: METHODS USED IN EVALUATING THE HUKILL-SCHMIDT MODEL

Transition Point

The transition between the first and second aspects of the Hukill-Schmidt model (22) is a function of the initial and final kernel humidities and the exponents of the second terms of each aspect. The model in differential form is:

\[
\frac{dt}{dm} = \frac{C_1}{(h-h_e)^a} + C_2 \frac{(h_o-h)^b}{h_o > h > h_{\chi}} \tag{17a}
\]

\[
\frac{dt}{dm} = \frac{C_1}{(h-h_e)^a} + \frac{C_3}{(h-h_e)^c} h_{\chi} > h > h_e \tag{17b}
\]

At the transition point it is assumed that: 1) time is continuous and 2) the drying rate is continuous. Equations 17a and 17b are set equal at \( h = h_{\chi} \):

\[
C_2 (h_o-h_{\chi})^b = C_3 (h_{\chi}-h_e)^c \tag{18}
\]

The difference (D) between the square of the values computed by 17a and by 17b is:

\[
D = [C_2 (h_o-h)^b]^2 - [C_3 (h-h_e)^c]^2 \tag{19}
\]

If this difference is zero at the transition point, then it must also be the minimum within the region around the transition point. Differenti-
iating $D$ with respect to $h$ gives:

$$\frac{dD}{dh} = -2 C_2 b (h_o - h)^{b-1} + 2 C_3 c/(h - h_e)^{c+1}$$  \hspace{1cm} (20)$$

when $dD/dh = 0$, then $h = h_x$:

$$C_2 b (h_o - h_x)^{b-1} = C_3 c/(h_x - h_e)^{c+1}$$  \hspace{1cm} (21)$$

Combining Equations 18 and 21 gives:

$$C_3/C_2 = (h_o - h_x)^b (h_x - h_e)^c = (b/c)(h_o - h_x)^{b-1} (h_x - h_e)^{c+1}$$  \hspace{1cm} (22)$$

Rearranging Equation 22 gives:

$$h_o - h_x = (b/c) (h_x - h_e)$$

$$h_x = (h_o - h_e)[c/(b+c)] + h_e$$  \hspace{1cm} (23)$$

Hukill and Schmidt fixed these exponents ($b=1, c=2$) and found the transition to occur at

$$h_x = (2/3) (h_o - h_e) + h_e$$

Numerical Integration Procedure

The relationship between moisture and relative humidity used in evaluating the integrals of the Hukill-Schmidt model, is given in graphical form. The following numerical procedure was used in this evaluation.

Let $y = f(x)$ be the function being considered. Then the term

$$\int_{a}^{b} f(x) \, dx$$
is the area bounded by:

\[ x = a \]
\[ x = b \]
\[ y = f(x) \]
\[ y = 0 \]

Dividing the interval \( b-a \) into \( n \) equal segments, the total area can be approximated by the sum of the areas of each segment. In mathematical form this gives:

\[
\int_{a}^{b} f(x) \, dx = (b-x_{n-1}) \left[ f(b) + f(x_{n-1}) \right]/2 + \ldots \\
+ (x_{2}-x_{1}) \left[ f(x_{2}) + f(x_{1}) \right]/2 \\
+ (x_{1}-a) \left[ f(x_{1}) + f(a) \right]/2
\]

\[ = \sum_{i=1}^{n} (x_i-x_{i-1}) \left[ f(x_i) + f(x_{i-1}) \right]/2 \quad (24) \]

Applying this method to the Hukill-Schmidt model results in the following equations:

\[
t = C_1 \sum_{i=0}^{n-1} (m_i-m_{i+1}) \left\{ \left[1/(h(m_i)-h_e)^a \right] + \left[1/(h(m_{i+1})-h_e)^a \right] \right\}/2 \\
+ C_2 \sum_{i=0}^{n-1} (m_i-m_{i+1}) \left\{ \left[h_0-h(m_i)^b \right] + \left[h_0-h(m_{i+1})^b \right] \right\}/2
\]

\[ h_0 \geq h \geq h_x \quad (25) \]
\[ t = C_1 \sum_{i=n_x}^{n-1} (m_i - m_{i+1}) \left\{ \frac{1}{(h(m_i) - h_e)^a} + \frac{1}{(h(m_{i+1}) - h_e)^a} \right\} / 2 \]

\[ + C_3 \sum_{i=n_x}^{n-1} (m_i - m_{i+1}) \left\{ \frac{1}{(h(m_i) - h_e)^c} + \frac{1}{(h(m_{i+1}) - h_e)^c} \right\} / 2 \]

\[ + t_x \quad h_x \geq h \geq h_e \]

(26)

The interval \((m_i - m_{i+1})\) is continuously decreased as the value of \((h(m_i) - h_e)\) approaches zero. This method was programmed for computation on the high-speed digital computer.
APPENDIX D: METHOD FOR ESTIMATING THE DRYING RATE

In examining the experimental data to determine the effects of the test variables on the drying curve, the drying rate is used. Use of the rate function is desirable because it gives an instantaneous picture of the drying pattern whereas the time function gives a cumulative picture.

The rate of drying ($r$) between two points can be expressed by the formula:

$$r_{1-2} = \frac{(m_1 - m_2)}{(t_1 - t_2)}$$  \hspace{1cm} (27)

In some instances, however, it is desirable to know the rate at a given data point. Since a high-speed digital computer was used for the analysis, a more elaborate method was developed.

Consider three consecutive data points: $P_1 = (m_1, t_1)$, $P_2 = (m_2, t_2)$ and $P_3 = (m_3, t_3)$ (Fig. 32). Let the distance ($D$) between the first two points be given by:

$$D = (m_1 - m_2)^2 + (t_1 - t_2)^2$$  \hspace{1cm} (28)

Next choose the point halfway between $P_1$ and $P_2$ and call it $P_a$. On the line connecting $P_2$ and $P_3$, lying at the angle

$$A = \text{Arctan} \left[ \frac{(m_2 - m_3)}{(t_2 - t_3)} \right]$$

from the horizontal, measure the distance $D/2$ from point $P_2$ and call this point $P_b$. Then the coordinates of $P_a$ and $P_b$ are:

$$P_a = (m_a, t_a) = \left[ \frac{(m_1 + m_2)}{2}, \frac{(t_1 + t_2)}{2} \right]$$  \hspace{1cm} (29a)
\[ P_b = (m_b, t_b) = (m_2 - (D/2) \sin A, t_2 + (D/2) \cos A) \quad (29b) \]

The rate at \( P_2 \) is:

\[ r_2 = \frac{(m_a - m_b)}{(t_a - t_b)} \quad (30) \]

This procedure was followed for all interior points.

The above procedure could not be used to determine the drying rate at the first and last points. For these special cases, Equation 27 was employed using the end point and the next adjacent point. The resulting rate was attributed to the end point.

The drying rate corresponding to the initial moisture by the above method was influenced greatly by the warm-up period. An apparent initial drying rate was determined to exclude the effects of the warm-up period. In determining the apparent initial rate, the first point and any succeeding points which exhibit a higher drying rate than the immediately preceding point are excluded. A straight line is then fitted through the next four points on a rate \((dm/dt)\) versus moisture plot and the intersection of this line with the initial moisture is called the apparent initial rate.
Fig. 32. Determination of rate of drying