SIMULATION OF LOW-TEMPERATURE CORN DRYING

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Received 23 November 1981.


This paper describes the development and validation of a model to simulate low-temperature corn drying under Ontario conditions. The model predicted the grain moisture profiles at different depths to within ± one percentage point of residual root mean square. Hourly weather records of Toronto and London for the period 1965–1978 were used to study the performance of the system. Weather conditions, harvest date, and initial moisture content were shown to influence greatly the performance of the low-temperature drying system when continuous airflow without supplemental heat was employed. Ambient drying of corn in Southern Ontario is not energy efficient in comparison with high-temperature drying in 62% of the years.

INTRODUCTION

Of all the drying methods, low-temperature drying is potentially the most energy efficient technique and most adaptable to use of such alternate energy sources as solar and biomass. In addition, Brown et al. (1979) showed that low-temperature drying produces high-quality grain with a high steeping index, test weight and viability, and with a negligible amount of kernel stress cracking.

Much past research has been aimed at producing computer models to simulate the low-temperature drying process; however, because the temperature and moisture gradients are much smaller than in high-temperature drying, the process is more complex with alternate drying and rewetting of the kernels. Most of the modelling attempts have used one of the following three basic approaches: (i) use of nonequilibrium models based on heat and mass balances involving partial differential equations; (ii) use of equilibrium models based on temperature and moisture equilibria between the drying air and the grain; and (iii) use of a combination of equilibrium and nonequilibrium models.

Nonequilibrium Models

Otten and Johnson (1979) tried to use the model of Bakker-Arkema et al. (1977) but found that very small time increments were necessary to prevent instability at low airflow rates and thus excessive computer time was needed.

In the same study, Otten and Johnson (1979) observed that the model of Meiering et al. (1977) resulted in overdrying of the bottom layers and that predicted values were not in agreement with experimental ones. It was decided that the model was too sensitive to the conditions of the input air and the model was modified by adding the thin-layer drying equation of Flood et al. (1972). The overdrying problem was eliminated, but the response to changes in air conditions was immediate and extreme. Recent results obtained in the present study showed that the above thin-layer equation was needed only when the grain moisture content was below 16% (WB).

Equilibrium Models

In equilibrium models, it is assumed that true equilibrium between the drying air and the grain is achieved in a certain time interval; however, there is evidence that this is not unconditionally true. Bloome and Shove (1971) formulated an equilibrium model and verified it with laboratory data. We observed that for a full-scale system, this model overpredicts the rates of both drying and rewetting. Similar observations were reported by Morey et al. (1979) and Van Ee and Kline (1979).

Thompson (1972) developed a simplified equilibrium model for low-temperature, low-airflow conditions. The model was verified by Kranzler (1977) using field data with grain corn of 18% initial moisture content.

It appears that the main disadvantage of using equilibrium models is that at low airflow rates true equilibrium conditions are not reached in the physical system, and especially not for the grain at the bin air inlet.

Combined Models

Most of these models incorporate equilibrium conditions with thin-layer drying and wetting equations. Thus, Flood et al. (1972) used the thin-layer drying equation developed by Sabbah (1968) and the wetting equation of del Giudice (1959). They neither checked the equilibrium conditions nor validated the model with experimental data. After making some modifications, Colliver et al. (1978, 1979) and Broder et al. (1979) used the model to optimize the drying system and develop a management scheme.

Morey et al. (1979) modified Thompson's (1972) model by incorporating Sabbah's (1968) thin-layer drying equation and Thompson's equations of sorption and desorption equilibrium moisture contents. They felt that the drying front progressed more slowly in the center of the bin than at other radial positions. To take care of the nonuniform airflow distribution, they used model airflow rates 20–30% lower than the average experimental flow rate and reported simulating the total moisture removed closely.

Van Ee and Kline (1979) employed the Morey model but added a fan management strategy plus other management criteria to provide the model with greater flexibility. They validated their model for high and low airflow rates with field data and concluded that the agreement was good.

Pierce and Thompson (1978) decided to use the equilibrium model when airflow rates were below 23.5 L/(m²·sec) or when the conditions of the drying air approached saturation and to use thin-layer drying equations for higher airflow rates.

Foster (1977) reworked the equation of Thompson's model by using the equation of Chung and Pfost (1967) for equilibrium moisture content, by correcting the psychrometric data for barometric pressure differences caused by local altitude, and by accounting for shrinkage during drying for a better comparison with actual samples obtained at constant depth intervals.

This paper describes the development and validation of a model to simulate low-temperature corn drying under Ontario conditions. The effects of weather conditions, harvest date and initial moisture content on drying performance were also discussed.
MODEL DEVELOPMENT

Since one of the purposes of developing a simulation model in the present work was to use it for microprocessor control of the drying system, the model had to be sufficiently simple to fit within the computational limitations of a microcomputer. For this reason, the nonequilibrium models were not used, even though many of them have been recently improved through application of different approaches and solution techniques.

After examining the models reported in the literature, it was concluded that Morey’s model is most satisfactory in describing the low-temperature drying process. The results obtained with this model were better than those obtained from the Otten-Johnson (1979), Meiering et al. (1977) and Bloome and Shove (1971) models. At this point it was decided to improve the Morey model by incorporating some recent developments and different solution techniques. The steps taken to obtain the final model and the corresponding computer program are presented below.

1. Thin-layer drying and rewetting equations were employed for the lower 13, 21, 33, 55, and 67% of the grain depth. After comparing the observed and predicted moisture profiles it was found that these equations are needed throughout the bed.

2. After using different thin-layer drying equations (Sabbah 1968; Rugumayo and Bakker-Arkema 1978; Mishra and Brooker 1979) and wetting equations (del Giudice 1959; Rugumayo and Bakker-Arkema 1978; Mishra and Brooker 1979) in the model, it was found that the thin-layer rewetting equation is also needed to describe accurately the condensation conditions in the bed. From the results it was concluded that Mishra and Brooker’s equations were most suitable.

The equivalent drying time technique suggested by Thompson (1967) was also included in the model. Since the drying conditions at a particular location change with each successive time step, each set of new conditions specifies a new thin-layer drying curve. The amount of drying completed was transferred to the new drying curve before calculating the new moisture content. Since absorption occurs at the same node during two successive time steps and occurs many times, the equivalent time method was also used for wetting conditions.

3. Various equilibrium moisture content equations were tried, but the desorption equation of Chung and Pfoist, as developed by Gustafson and Hall (1974), was found to give the lowest value of the sum of squares of the differences between predicted and observed grain moisture contents.

For sorption, only one equilibrium moisture content equation is available. It was developed by Thompson and quoted by Morey et al. (1979).

4. A shrinkage model was included in the drying model because Otten and Johnson (1979) noticed a 7–11% decrease in the depth of grain bed after drying. As a result of shrinkage, the grain samples drawn from the sampling tubes throughout the course of the experiment did not represent the same layer.

To predict and correct this change in bed depth, a shrinkage model was developed by calculating the change in kernel volume with the equation of Fortes and Okos (1979), the porosity from the bulk density equation of Kazarian and Hall (1963) and the kernel density from the equation of Chung and Converse (1971). The resulting shrinkage model predicted the experimental change in bed depth within ±7%.

5. In low-temperature drying simulation, the time increment and layer thickness must be chosen to approximate closely the requirement of constant air properties over that depth or that time span. A time step of 8 h can be used without introducing a significant error, although greater accuracy is obtained with a 3-h step at the expense of more computer time. Determined optimum layer thickness was between 0.075 and 0.080 m.

6. The analytical models of grain deterioration developed by Thompson (1972) from the data reported by Steele et al. (1969) and Saul (1970) were used to calculate the loss of dry matter during the drying period. Aflatoxin development was obtained by the criterion presented by Ross et al. (1979), who suggested that aflatoxin would develop in the top layer of grain when the equilibrium relative humidity is above 85% and the temperature is in the range of 13 to 41°C for more than 48 h.

7. The pressure drop in air flowing through grain corn was obtained from the model presented by Hukill and Ives (1955) with a pack-factor of 1.5. This value was then used to calculate the energy consumption during aeration by assuming the fan and motor efficiency of 60 and 90%, respectively.

MODEL VALIDATION

The suitability of the final model in predicting moisture changes in a deep bin was examined by using data obtained by Otten and Johnson (1979) and Otten and Brown (1980) during field tests in the fall of 1978 and 1979. The experimental low-temperature drying system consisted of two 5.9 m diameter by 6.2 m high Westelo — Rosco bins. Each bin was fitted with a fully perforated floor and an axial drying fan, 680 mm diameter, driven with a 9.3 kW electric motor. One of the bins used solar-heated air to dry grain while the other one used ambient air. In each case provision was made for additional heat using a set of three 10 kW electric heaters. Provision was also made to use any of these heaters based on additional heat requirement.

In 1978, the initial moisture content was sufficiently low to allow filling of the bins with corn directly from the field; however, in 1979 the initial moisture content was about 29% and the corn passed through a continuous flow, high-temperature dryer before it was put hot into the two bins. It was then dried from 20% to about 14.5% with the low-temperature system.

During the 1978 drying period only ambient or solar-heated air was used but because the 1979 season was considerably cooler and wetter, one 10-KW heater was needed during the nights to raise the drying potential of the ambient air.

The average experimental conditions and results are summarized in Table I. The

<table>
<thead>
<tr>
<th>TABLE I. FIELD TESTS OF LOW-TEMPERATURE DRYING SYSTEMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient</td>
</tr>
<tr>
<td>1978</td>
</tr>
<tr>
<td>----------------------------------------------------------</td>
</tr>
<tr>
<td>Initial mass of grain (tonne)</td>
</tr>
<tr>
<td>Average initial moisture content (% WB)</td>
</tr>
<tr>
<td>Initial depth of grain (m)</td>
</tr>
<tr>
<td>Avg airflow rate (L/sec)</td>
</tr>
<tr>
<td>Avg air velocity (m/sec)</td>
</tr>
<tr>
<td>Drying time (h)</td>
</tr>
<tr>
<td>Avg fnal moisture content (% WB)</td>
</tr>
<tr>
<td>Final depth of grain (m)</td>
</tr>
<tr>
<td>Shrinkage (%)</td>
</tr>
<tr>
<td>Final mass of grain (tonne)</td>
</tr>
<tr>
<td>Amount of water removed (tonne)</td>
</tr>
</tbody>
</table>

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measured moisture content profiles (at different depths) for ambient air drying in 1978 and solar heated air drying in 1979 are compared with predicted profiles in Figs. 1 and 2. The predicted profiles were obtained with the simulation model using hourly recordings of drying air temperature and relative humidity as input data. The plots show that the predicted values follow the same trend as the measured ones. However, agreement at a few locations is poor. Similar agreement was found for the other two drying situations.

An analysis of all the results showed that the difference between computed and measured moisture content values varied between ±2 percentage points (WB) with 60% of the residuals being between ±0.5 percentage points. The root mean square values of the residuals varied between 0.5 and 1 percentage point for the four tests.

Observed moisture profiles were also compared with the predicted profiles from models of Meiering et al. (1977), Otten and Johnson (1979), Bloome and Shove (1971) and Morey et al. (1979). The root mean square values of the residuals were 10–35% higher than those obtained from the present model.

The average moisture contents of the corn in the bin on different days during each of the four drying tests is presented in Fig. 3. Again, the agreement between measured and predicted values is satisfactory.

Despite the encouraging results, complete validation of the model with actual field data is difficult. Aside from the uncertainties inherent in the various parameteric equations used in the model, there are experimental errors and interpretations to contend with. For example, Morey et al. (1979) decided to use a lower airflow rate in the model than observed in the experimental system because they felt that the grain at the center of the bin, where they took their samples, was subjected to a lower airflow rate. After traversing the top of the bed with a cone-anemometer device, Otten and Johnson (1979) obtained air velocity results showing that the velocity in the center is lower than elsewhere; however, the grain samples were obtained from ports in the north side of the bins where the velocity is higher than the average value. Nevertheless, we also found that the assumption of a lower-than-measured flow-rate produced better simulation results. Therefore, it seems that either the effect of the drying air on successive layers of grain is reduced by the presence of previous layers in the bed, a phenomenon which is not accounted for by the thin-layer equation, or there are significant errors in airflow rate measurements. Otten and Johnson (1979) did indeed find that the cone-anemometer method and the fan performance method gave about 20% higher values than those obtained from static pressure drop measurements and American Society of Agricultural Engineers Standard D272 (1979).

For the present study, it was decided to use the effective airflow rates as determined by the simulation model for the 1978 tests. These values plus those reported by Morey et al. (1979) were used to produce the following regression model with an $r^2$ value of 0.997.

\[
Q_e = 0.7648 Q_o - 1.3418 \times 10^{-3} Q_o^2
\]
Figure 3. Comparison of the predicted and observed average grain moisture contents during drying in 1978 and 1979.

Where $Q_e$ and $Q_o$ are the effective and observed volumetric airflow rates in L/(m$^3$-sec), respectively.

MODEL APPLICATION

After formulating the drying model and verifying it with the 1978 and 1979 field data, the model was used to investigate the suitability of low-temperature corn drying for Southern Ontario. For this purpose, hourly weather data for the period of 1965–1978 were obtained from the Canadian Climatic Centre for the Toronto and London areas. These data were used in the model to determine the minimum airflow rates required to dry grain corn with $\pm0.5\%$ dry matter deterioration in the upper 10% of the bin. This minimum value was calculated using a one-dimensional optimization approach in which a Golden section search was employed with successive parabolic interpolations (Mittal 1979). In addition to the minimum airflow rates, the corresponding fan-hours and energy consumptions were also calculated from the simulation results.

The following operating steps and assumptions were used in the study:

1. Grain corn with an initial mass of 93 tonne was placed in a single fill on a 26.8-m$^2$ perforated bin floor to a depth of 4.4 m.
2. All corn had the same initial moisture content of 22% except for simulation runs to study the effect of corn initial moisture content; and a temperature equal to the average ambient temperature of the last 24 h.
3. Temperature rise due to fan heat and frictional energy was calculated for each airflow rate. Based on a combined fan and motor efficiency of 54%, 46% of the total temperature rise was added in the plenum and the remaining rise was divided uniformly over the grain depth. This is accomplished by an additional term in the energy balance as suggested by Morey et al. (1979).

Systems requiring static pressures greater than 1900 Pa were considered impractical. Axial fans were considered up to 1000 Pa static pressure and centrifugal fans for higher pressure.

4. The corn harvesting date was 15 Oct. except for simulation runs to study the effect of harvesting date. A time increment of 8 h and a depth increment of 0.44 m was used in the simulation to save computer time.

5. The fan management practice was formulated after careful examination of local practices and climatological changes. The fall shut-off conditions are given in Table II. Winter and spring management practices are described below.

6. Continuous fan operation without supplemental heat was assumed. Drying was discontinued when the average moisture content was $\approx15\%$.

7. Calculations of dry matter deterioration during the winter months were based on the fall shut-off conditions.

After incorporating the above seven criteria, the model was used to perform the following simulation studies:

1. The effect of weather on the systems performance using 13 yr of weather data.
2. The effects of fall starting date, initial moisture content, and spring starting date. For this study, 5 yr were selected based on minimum specific energy consumption. These included two poor drying years (>5.0 MJ/kg of water removed), two good drying years (<2.0 MJ/kg), and one average drying year (3.8 and 3.3 MJ/kg for London and Toronto, respectively). The following values of these parameters were used while all other assumptions and operating conditions were held constant: (i) fall starting dates: 1 Oct., 15 Oct., 1 Nov. and 15 Nov.; (ii) initial moisture contents: 22, 24 and 26%; (iii) spring starting dates: 1 Apr. and 15 Apr.

RESULTS AND DISCUSSION

Effect of Weather

Table III shows the minimum airflow rate, fan operating time and specific energy consumption versus years for London and Toronto assuming a starting date of 15 Oct. and an initial moisture content of 22%. Table IV lists the variations in performance for various years.

The minimum airflow rate is shown to vary from 13.4 to 30.0 L/(m$^3$-sec of grain) for London and from 12.4 to 26.1 L/
TABLE III. SYSTEM PERFORMANCE PARAMETERS FOR VARIOUS YEARS FOR LONDON AND TORONTO (22% INITIAL MOISTURE CONTENT AND 15 OCT. HARVEST DATE)

<table>
<thead>
<tr>
<th>Year</th>
<th>Airflow rate (L/(m²·sec))</th>
<th>Fan operating time (h)</th>
<th>Specific energy consumption (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>London</td>
<td>Toronto</td>
<td>London</td>
</tr>
<tr>
<td>1965</td>
<td>18.7</td>
<td>20.5</td>
<td>2430</td>
</tr>
<tr>
<td>1966</td>
<td>16.1</td>
<td>15.6</td>
<td>2560</td>
</tr>
<tr>
<td>1967</td>
<td>17.6</td>
<td>18.4</td>
<td>1620</td>
</tr>
<tr>
<td>1968</td>
<td>23.7</td>
<td>21.8</td>
<td>2920</td>
</tr>
<tr>
<td>1969</td>
<td>18.0</td>
<td>16.4</td>
<td>1910</td>
</tr>
<tr>
<td>1970</td>
<td>25.7</td>
<td>17.6</td>
<td>1460</td>
</tr>
<tr>
<td>1971</td>
<td>30.6</td>
<td>26.1</td>
<td>1620</td>
</tr>
<tr>
<td>1972</td>
<td>25.5</td>
<td>23.8</td>
<td>1390</td>
</tr>
<tr>
<td>1973</td>
<td>21.1</td>
<td>21.1</td>
<td>2930</td>
</tr>
<tr>
<td>1974</td>
<td>17.0</td>
<td>16.4</td>
<td>2040</td>
</tr>
<tr>
<td>1975</td>
<td>22.6</td>
<td>21.6</td>
<td>1590</td>
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<tr>
<td>1976</td>
<td>13.4</td>
<td>12.4</td>
<td>2170</td>
</tr>
<tr>
<td>1977</td>
<td>22.3</td>
<td>18.2</td>
<td>1660</td>
</tr>
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</table>

(m³·sec) for Toronto. The airflow rate for London is thus generally higher than for Toronto. This is because the ambient temperatures at the start of drying are higher for London and, thus, higher airflow rates are needed to prevent dry matter decomposition.

A further analysis showed that an airflow rate of 26.8 L/(m³·sec) is sufficient for about 85% of the years in London and 100% in Toronto. The high flow rates for 1 to 2 yr out of 13, were due to unreasonably high ambient temperatures during the initial drying period followed by a wet period. It is interesting to note that Pierce and Thompson (1979) found that an airflow rate of 28.7 L/(m³·sec) was needed for Lincoln, and 18.9 L/(m³·sec) for central Iowa for a probability of success of 84 and 90%, respectively, for a moisture content of 24% and a harvest date of 15 Oct. For southern Ontario, still higher airflow rates will be required for initial grain moisture content greater than 22%. A value of 24.5 L/(m³·sec) was calculated by Fraser (1979) for the worst year in London under similar conditions with the model of Thompson (1972).

Fan operating times vary from 1390 to 2930 h for London and from 1590 to 2540 h for Toronto. The fan shut-off dates for London were between 16 Nov. and 11 Dec. and, for Toronto, 22 Nov. and 14 Dec. The November shut-off dates were due to an early onset of winter. In most years, about 50% of the total fan operating time was needed in the spring; although, this requirement varied from 44 to 74% for London and from 45 to 73% for Toronto. In any 1 yr the variation in total fan operating time for London and Toronto did not vary significantly.

The specific energy consumption for London was between 1.4 and 7.8 MJ/kg of water removed, and between 1.1 and 5.5 MJ/kg of water removed for Toronto. The specific energy consumption dropped to 5.3 from 9.9 MJ/kg as the harvesting date was moved from 1 Oct. to 15 Nov.

It is evident that the high ambient temperatures of the early fall require higher airflow rates to prevent excessive dry matter deterioration. The 1971 London example showed that 82% of the dry matter loss occurred in the fall, 8% in the spring and 10% in the winter for an 1 Oct. harvesting date and that these values for a 15 Nov. date were, respectively, 25, 26 and 50%.

Fraser (1979) calculated that 15 Oct. is the most expensive date to start drying in London. Similar results were reported by many investigators (Bakker Arkema et al. 1977; Pierce and Thompson 1979; Morey et al. 1979) for the various corn growing areas in the U.S.A.

The results in Table V also indicate that the greatest reduction in airflow rate and energy consumption due to a delay in starting date is observed for the poor drying years.

From an energy point of view, low-temperature drying should not be started in southern Ontario until 1 Nov. unless layer filling is used to increase the effective airflow rate; however, this recommendation must be coupled with field loss criteria.
TABLE V. EFFECT OF CORN HARVESTING DATE ON SYSTEM PERFORMANCE (22% INITIAL MOISTURE CONTENT)

<table>
<thead>
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</tr>
</thead>
<tbody>
<tr>
<td>1 Oct.</td>
<td>30.7</td>
<td>26.1</td>
<td>20.5</td>
<td>20.6</td>
<td>17.4</td>
<td>28.1</td>
<td>23.9</td>
<td>23.5</td>
<td>21.2</td>
<td>12.8</td>
</tr>
<tr>
<td>15 Oct.</td>
<td>30.0</td>
<td>28.5</td>
<td>22.3</td>
<td>17.6</td>
<td>13.3</td>
<td>26.1</td>
<td>23.8</td>
<td>21.5</td>
<td>16.4</td>
<td>12.4</td>
</tr>
<tr>
<td>1 Nov.</td>
<td>22.7</td>
<td>26.0</td>
<td>18.8</td>
<td>17.6</td>
<td>16.1</td>
<td>18.7</td>
<td>20.8</td>
<td>20.0</td>
<td>19.7</td>
<td>13.1</td>
</tr>
<tr>
<td>15 Nov.</td>
<td>25.1</td>
<td>32.8</td>
<td>20.0</td>
<td>26.6</td>
<td>17.8</td>
<td>24.4</td>
<td>27.2</td>
<td>26.6</td>
<td>18.3</td>
<td>12.7</td>
</tr>
</tbody>
</table>

1. **Minimum airflow rate (L/(m³·sec))**

2. **Fan operating time (h)**

3. **Specific energy consumption (MJ/kg)**

because a lower yield could easily offset the energy saved.

**Effect of Initial Moisture Content**

Table VI shows the effect of initial moisture content on airflow rate, fan operating time, and energy consumption for London and Toronto. The starting date for these results was 15 Oct.

The simulation results show that in poor drying years it is not practical to dry grain corn with an initial moisture content greater than 22% under Ontario conditions because of the high airflow rates and static heads required for a grain bed depth of 4.4 m. Many researchers have suggested that, under adverse weather conditions or wetter grain, the bins should be only partially filled to obtain high airflow rates without excessive static heads; however, since a farmer does not know the kind of drying season in advance, he must design his drying system so that it will successfully dry his crop in, say, 90% of the time. This is especially important in southern Ontario where the weather patterns are less predictable because of the Great Lakes.

The results also show that the minimum airflow rate and energy consumption both increase with an increase in initial moisture content from 22 to 26% while the fan operating time decreases. For example, in 1976 (a good drying year) in London, the airflow rate increased from 13.3 to 23.7 L/(m³·sec) and energy consumption from 1.4 to 2.6 MJ/kg, while fan operating time decreased from 2170 to 1570 h.

In a few good drying years, the initial moisture content can be as high as 26% before the full-bin, low-temperature drying method fails. However, since the average initial moisture content is often in excess of 26% and because the future weather conditions are unknown, it is recommended that farmers use combination drying with low-temperature drying starting at 22-24% moisture content.

A further analysis indicated that with a 1 Nov. starting date, an airflow rate of 26 L/(m³·sec) is sufficient to dry grain corn safely from 22 to 15% moisture content in all years in London and Toronto. Of course, it is not practical to delay the entire harvest until this date.

It is clear that an airflow rate of about 26 L/(m³·sec) is needed to ensure that grain corn at 22% moisture content can be dried under nearly all Ontario conditions. To make the low-temperature drying system efficient in every year, some form of control and management practice must be used other than continuous fan operation without supplemental heat.

**Effect of Spring Starting Date**

Table VII depicts the effect of the spring starting date on minimum airflow, fan operating time, and energy consumption for Toronto and London. The harvesting date was 15 Oct. and the initial moisture content was 22%.

Delaying the spring starting date from 1 Apr. to 15 Apr. resulted in reduced fan operating time for all years in London and Ontario.
for a few years in Toronto, and reduced energy consumption for poor drying years. No significant changes were noticed for good drying years. It appears that a greater amount of rewetting occurs with an April 1st date.

For Ontario conditions, the spring starting date may be delayed until the middle of April; however, in practice, the long-range weather forecast should be used to determine the actual starting date.

CONCLUSIONS AND RECOMMENDATIONS

The conclusions and recommendations derived from the model development and simulation work are summarized:

1. The equilibrium model overpredicts the rate of drying and wetting especially on the bottom layers; while the nonequilibrium models require large amounts of computer times at the low airflow rates encountered in low-temperature drying systems.

2. The combination of the equilibrium model with thin-layer drying and wetting equations was used to predict moisture profiles in low-temperature drying to within ± 1 percentage point of residuals root mean square.

3. A shrinkage model was developed based on the volume change of kernels during drying. This model was shown to predict the change in grain depth within ± 7%.

4. The harvest date, initial grain moisture content and the weather conditions were shown to greatly influence the performance of a low-temperature drying system.

5. An airflow rate of 26.0 L/(m²·sec) is suitable for about 85% of the years in London and 100% in Toronto for harvesting date of 15 Oct. This high airflow rate is due to the warm moist weather during the drying period.

6. Energy is saved by delaying the harvest date from 1 Oct. to 1 Nov. because both the airflow rate and fan operating time are reduced.

7. The minimum airflow rate and energy consumption increase with an increase in the initial moisture content from 22 to 26%, while the fan operating time decreases.

8. Low-temperature drying in Southern Ontario using continuous fan operation without supplemental heat is not energy efficient in comparison with high-temperature drying in 62% of the years for the London and Toronto areas.

The main conclusion of this work is that in Southern Ontario, ambient drying of grain corn is not likely to result in significant energy savings as compared to high-temperature drying in all the years, unless some form of automatic control of the drying process is introduced. Such a control system must either introduce supplemental heat when adverse weather conditions result in rewetting or stop the fans when too much heat is needed to continue drying. It must also ensure that the grain is kept cool by periodic ventilation during prolonged periods of wet weather.

ACKNOWLEDGMENTS

The financial support by the Ontario Ministry of Agriculture and Food and the Ontario Ministry of Energy is greatly appreciated. Special thanks are extended to Dr. Claire Rennie, Assistant Deputy Minister, for his interest and cooperation.

REFERENCES


TABLE VII. EFFECT OF SPRING START DATE ON SYSTEM PERFORMANCE

<table>
<thead>
<tr>
<th>Spring start date</th>
<th>London</th>
<th>Toronto</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Apr.</td>
<td>30.0</td>
<td>28.5</td>
</tr>
<tr>
<td>15 Apr.</td>
<td>30.0</td>
<td>28.7</td>
</tr>
<tr>
<td></td>
<td>1 Apr.</td>
<td>1620</td>
</tr>
<tr>
<td></td>
<td>15 Apr.</td>
<td>1300</td>
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<td></td>
<td>1 Apr.</td>
<td>7.8</td>
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<td>15 Apr.</td>
<td>6.3</td>
</tr>
<tr>
<td>1. Minimum airflow rate (L/(m²·sec))</td>
<td></td>
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<tr>
<td>2. Fan operating time (h)</td>
<td></td>
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<tr>
<td>3. Specific energy consumption (MJ/kg)</td>
<td></td>
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</tr>
</tbody>
</table>