Analysis of Continuous-flow Grain Dryers

F.W. Bakker-Arkema*, M.D. Montross*, Liu Qiang* and D.E. Maier†

Abstract

The high-temperature continuous-flow dryer is the prevalent dryer type in the major grain-producing countries. The choice of a particular model is frequently based on the initial cost, rather than on technical factors such as energy efficiency and grain quality. This has led at times to the employment of low-quality dryers, and to the production of inferior-grade grain and the consumption of excessive fossil-fuel energy. This paper shows that the dryer-manufacturing industry currently markets reasonably-priced, energy-efficient dryers which are able to produce excellent quality grain.

Crossflow, mixed-flow, and concurrent-flow are at present the primary high-temperature dryer types. Simulation modelling is routinely used today in the industry for analysis and design, resulting in their improved grain-quality and energy-efficiency characteristics.

The modern crossflow dryer is suitable for drying maize as feed; it is less expensive than mixed-flow and concurrent-flow dryers. For the drying of rice (and food maize), mixed-flow and concurrent-flow dryers are recommended because of their superior grain-quality characteristics. Of these, the concurrent-flow models have, in general, the best energy efficiency.

Several unconventional high-temperature dryers are occasionally used commercially for the drying of grains. Included in this group are the steam, the rotary, and the fluidised-bed dryers. Although each of these dryer types has certain advantages, their high initial and operating costs have thus far prevented market penetration.

Drying is one of the essential steps in the postharvest technology of grains, especially of maize and rice which almost always require mechanical drying. Grains are dried on the farm and off the farm, depending mainly on the country of production. For instance, in the USA the bulk of the maize is farm-dried; in France, almost all the maize is dried off the farm at local grain depots. This paper assesses the state-of-the-art of off-farm grain drying, and its specific needs for design improvement.

Off-farm dryers are considered to be of the high-temperature continuous-flow type, and to have a capacity of at least 12.5 t/hour. Usually, this excludes all but the largest in-bin drying systems.

The main off-farm dryer types are: (1) the crossflow dryer, (2) the mixed-flow dryer, and (3) the concurrent-flow/counterflow dryer (see Fig. 1). Each dryer type is able to dry maize rice and other grains. Each type has specific advantages and disadvantages. The dryer-selection criteria differ somewhat from country to country, and from crop to crop. For instance, a 1995 Chinese tender for the purchase of a series of high-temperature maize dryers ranks and weights the dryer-characteristics as follows (CNIIEC 1995): (1) initial price—60%, (2) energy consumption—5%, (3) kernel breakage—5%, (4) moisture gradient at dryer exit—5%, (5) life expectancy—4%, (6) dryer type—3%, (7) increase in stress-cracked kernels—3%, (8) level of automatic control—3%, (9) kernel-temperature at dryer exit—2%, (10) service record—10%. Thus, the price factor (60%) far outweighs the technical factors (30%) and the service factor (10%), and the least expensive dryer is likely to be selected for the drying of maize in northeastern China, regardless of the model's grain-quality and energy-efficiency characteristics. In general, the weighting scale of the various economic/technical/service factors is decisive in the selection of the high-temperature dryer at a grain facility.

Analyses of dryer designs are today routinely conducted by computer simulation; models of the major dryer types have been available in the literature for a decade (Brooker et al. 1992). Simulation modelling has not led to revolutionary new dryer designs but has resulted in evolutionary improvement of existing dryer types. This is best illustrated by comparing the energy-efficiency and grain-quality characteristics of

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1970-vintage crossflow dryers and 1990 models: significant improvement has occurred with respect to both dryer-quality parameters.

Grain Moisture Content

High-temperature grain dryers are commonly rated for capacity on the basis of 10-point moisture removal from maize, i.e. from 25 to 15% moisture content (wet basis). No mention is made that the quoted moistures are average moisture contents. It is assumed that the variation in moisture content of the maize kernels entering a dryer is small. However, this is not the case, as is shown in Table 1 in which the average moisture content, the moisture content range, and the standard deviation of 50 kernels on an ear are tabulated for the tip/middle/butt kernels of an early and a late maize variety. The difference in the moisture content of the wettest and driest kernels is 27.5% for the early variety, and 32.0% for the late variety. The tip kernels are on average about 5% drier than the butt kernels. Just after high-temperature drying, the difference in moisture content between the kernels is still large, as the data in Table 2 show.

The moisture range narrows and the standard deviation diminishes during storage (see Tables 3 and 4).

Dryer Types

Crossflow dryers

Crossflow dryers are the most popular dryer type in North America. They have a plenum surrounded by a relatively thin grain column; hot air traverses the grain perpendicular to the downward flow of the grain. Cooling of grain takes place in the bottom section of the grain column. Crossflow dryers are often called tower or column dryers.

Crossflow dryers do not dry grain uniformly. Significant moisture and temperature gradients exist across the grain column at the moment the drying process is discontinued. During the cooling cycle the degree of non-uniformity decreases, but a definite moisture differential among the kernels still exists when the grain leaves the dryer, notwithstanding the fact that the average moisture content may have reached the desired level.

Recent design advances in crossflow dryers have improved the grain-quality characteristics of this model type. Airflow reversal has been incorporated in some crossflow dryers in order to offset the moisture and temperature differentials in the grain column. Grain inverters turn the overheated grain at the air-inlet side to the air-exhaust side of the column, and thus reduce overdrying/overheating. A new feature added recently to the basic crossflow design—tempering—improves the quality of crossflow-dried grain.

Modern crossflow dryers with air recycle, grain tempering, and grain inverting are able to dry wet grain at high throughput and moderate energy efficiency, and can produce dried grain with moderate moisture differentials among the kernels. For feed grain, the crossflow dryer is a good choice.

In-depth analyses of crossflow-dryer designs can be made by employing a differential-equation-based model of the following type (Brooker et al. 1992):

\[
\frac{\partial T}{\partial x} = -\frac{h_u}{G_v + G_a c_w} (T - \theta) \\
\frac{\partial \theta}{\partial y} = \frac{\kappa_a}{G_v p + G_a c_w} (T - \theta) \\
+ \frac{h_{ex} + c_0 (T - \theta)}{G_v p + G_a c_w} \frac{\partial W}{\partial x} \\
\frac{\partial W}{\partial x} = \frac{G_p}{G_a} \frac{\partial M}{\partial y} \\
\frac{\partial M}{\partial t} = \text{a single-kernel drying equation}
\]
Table 1. Average kernel moisture content (%), moisture content range, and standard deviation of 50 kernels on an ear of an early and late variety maize in the midwestern USA.

<table>
<thead>
<tr>
<th>Location</th>
<th>Late variety</th>
<th>Early variety</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average moisture content</td>
<td>Moisture content range</td>
</tr>
<tr>
<td>Tip</td>
<td>25.0</td>
<td>8.5–36.5</td>
</tr>
<tr>
<td>Middle</td>
<td>28.3</td>
<td>10.5–38.0</td>
</tr>
<tr>
<td>Butt</td>
<td>30.4</td>
<td>12.5–40.5</td>
</tr>
</tbody>
</table>

Table 2. Standard deviation and moisture content (%) range of maize dried in a commercial crossflow dryer.

<table>
<thead>
<tr>
<th>Inlet</th>
<th>Average moisture content</th>
<th>Standard deviation</th>
<th>Moisture content range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>22.7</td>
<td>4.51</td>
<td>12.5–34.5</td>
</tr>
<tr>
<td></td>
<td>21.8</td>
<td>3.80</td>
<td>12.0–33.0</td>
</tr>
<tr>
<td></td>
<td>21.0</td>
<td>3.13</td>
<td>14.0–31.0</td>
</tr>
<tr>
<td>Outlet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>14.5</td>
<td>3.17</td>
<td>8.5–24.5</td>
</tr>
<tr>
<td></td>
<td>13.9</td>
<td>3.44</td>
<td>8.0–28.5</td>
</tr>
<tr>
<td></td>
<td>12.7</td>
<td>4.23</td>
<td>7.0–31.0</td>
</tr>
</tbody>
</table>

Table 3. Short-term change in the moisture content (%) range and standard deviation of maize after crossflow drying (average m.c. = 14.5%).

<table>
<thead>
<tr>
<th>Time (hours)</th>
<th>Moisture content range</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>9.0–30.5</td>
<td>3.75</td>
</tr>
<tr>
<td>3</td>
<td>10.0–21.5</td>
<td>2.63</td>
</tr>
<tr>
<td>20</td>
<td>10.0–24.5</td>
<td>2.38</td>
</tr>
<tr>
<td>27</td>
<td>10.0–18.5</td>
<td>2.08</td>
</tr>
<tr>
<td>45</td>
<td>11.0–17.5</td>
<td>1.74</td>
</tr>
<tr>
<td>50</td>
<td>9.5–16.5</td>
<td>1.63</td>
</tr>
<tr>
<td>68</td>
<td>10.0–17.5</td>
<td>1.50</td>
</tr>
<tr>
<td>92</td>
<td>11.0–17.0</td>
<td>1.38</td>
</tr>
<tr>
<td>114</td>
<td>10.5–16.0</td>
<td>1.21</td>
</tr>
<tr>
<td>122</td>
<td>11.5–16.5</td>
<td>1.24</td>
</tr>
<tr>
<td>450</td>
<td>11.5–16.5</td>
<td>1.03</td>
</tr>
</tbody>
</table>

Table 4. Long-term change in the average moisture content (%), moisture content range, and standard deviation of maize stored in a 1500 t bin under Michigan conditions.

<table>
<thead>
<tr>
<th>Date</th>
<th>Average moisture content</th>
<th>Moisture content range</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Nov. 93–30 Nov. 93</td>
<td>14.5</td>
<td>9.0–30.5</td>
<td>3.75</td>
</tr>
<tr>
<td>10 Jan. 94</td>
<td>16.4</td>
<td>11.0–18.5</td>
<td>1.30</td>
</tr>
<tr>
<td>17 Feb. 94</td>
<td>15.2</td>
<td>11.0–17.5</td>
<td>1.06</td>
</tr>
<tr>
<td>22 Mar. 94</td>
<td>13.6</td>
<td>10.0–15.0</td>
<td>1.15</td>
</tr>
<tr>
<td>25 Apr. 94</td>
<td>13.2</td>
<td>10.5–15.5</td>
<td>1.07</td>
</tr>
</tbody>
</table>

Solution of the model for a specific crossflow dryer establishes the approximate values of such parameters as: (1) the grain retention time, (2) the minimum and maximum kernel temperatures, (3) the minimum and maximum kernel moistures, and (4) the energy efficiency.

Airflow reversal, tempering, and grain inverting were first investigated by simulation (Pierce and Thompson 1981), and have subsequently been applied successfully to commercial crossflow dryer designs (FFI Corporation, Indianapolis, Indiana, personal communication, 1995).
Concurrent-flow dryers

The concurrent-flow dryer design is relatively new; it has one or more concurrent-flow drying sections, and one counterflow cooling section. In a concurrent-flow section, the grain and drying air flow in the same direction, in the counterflow cooler in the opposite direction.

With the exception of a small, one-stage on-farm concurrent-flow model, concurrent-flow dryers have two or three concurrent-flow drying zones. A tempering zone is located between successive drying sections. The ability to employ different air temperatures in the different stages is an inherent advantage of this dryer type.

A concurrent-flow/counterflow dryer has alternate concurrent-flow and counterflow drying sections. Dryers of this type are of Chinese design, and usually are multi-tower units. Because of the relatively poor grain-quality characteristics of this dryer, it is not further discussed.

The most distinguishing feature of the concurrent-flow dryer is the uniformity of the drying process. Every kernel undergoes the same heating/drying/tempering/cooling treatment, unlike in crossflow and mixed-flow dryers. The temperature of the drying air is much higher than in the other dryers because the wet grain is subjected to the hot drying air not for hours (crossflow dryers) or minutes (mixed-flow dryers), but only seconds. Therefore, the grain does not approach the temperature of the drying air, as it does in the other dryer types.

The uniform, relatively gentle drying and cooling processes in concurrent-flow dryers, and the built-in tempering treatment(s), result in dried grain of superior quality. The percentage of stress-cracked kernels in concurrent-flow dryers is less than in mixed-flow and crossflow-dried grain.

Mixed-flow dryers are the predominant dryer type in western Europe and Latin America. Grain is dried in mixed-flow dryers by a mixture of crossflow, concurrent, and counterflow processes. The grain flows over a series of alternate inlet and exhaust air ducts. This results in fairly uniform drying, and therefore in relatively uniform grain moisture content and quality. The drying temperature in mixed flow dryers is higher than in crossflow dryers because the grain is not subjected to the high temperature for as long.

It has recently been shown that there is a significant difference in the retention time and grain-temperature history between the kernels as they pass through a mixed-flow dryer (Liu 1993). This leads to a higher
than expected spread in the moisture content and temperature of the grain exiting the dryer.

The difference in design between different mixed-flow dryer models centres around the duct size/spacing/pattern specifications. No comparative studies have been published on these design modifications with respect to fuel consumption, grain-quality characteristics, and capacity (i.e. throughput per unit of dryer volume). Therefore, claims by manufacturers of 'best duct design' are impossible to verify.

Mixed-flow dryers are more expensive to manufacture and require more extensive air-pollution equipment than crossflow dryers.

During the mixed-flow drying process, the grain kernels are subjected to a continuously-changing pattern of repeated crossflow concurrent-flow and counterflow drying treatments. Therefore, a mixed-flow dryer simulation model consists of a combination of these three submodels (Liu 1993).

The mixed-flow drying model has recently been utilised for the design of tapered airducts in a mixed-flow maize dryer (Cao 1993).

Miscellaneous dryer types

In addition to the three major grain dryer types, i.e. crossflow, mixed-flow, and concurrent-flow, several other dryers are used occasionally for grains, often only at the research level. Spouted-bed, fluidised bed, and microwave dryers are examples; they have not (yet) proven to be economical as high-temperature dehydration devices for grains.

Rotary dryers are employed successfully in drying rice, mainly parboiled rice. The uniform drying treatment of the kernels is an advantage. However, the initial and maintenance costs of these dryers are high, and thus they do not compete with the more conventional grain-dryer types.

The steam dryer is a recent Chinese invention, and is popular in certain regions of northeastern China. A steam dryer usually consists of 3 to 4 towers in series. Each tower contains in its upper section a series of steam pipes, and in its lower section a number of inlet/outlet airducts. The grain is heated by conduction as it flows over the steam-heated pipes, and is subsequently treated with ambient or slightly-heated recycled drying-air. The grain retention time is long (4–6 hours for 10-point moisture removal) due to the relatively low grain temperatures, resulting in superior grain quality. The high initial cost of a steam dryer is likely to prevent adoption of this dryer type outside of China.

Rotary-dryer models have been developed in the chemical engineering industry (Kelly 1987). However, they have not been applied to the design and analysis of rotary grain-dryers.

The authors have not been able to find a steam-dryer model for grain in the literature.

Dryer Comparison

Drying temperatures

The drying-air temperatures employed in high-temperature grain dryers depend on the dryer type and the grain variety. Table 5 contains values of the temperatures measured recently in maize dryers at elevator/grain-depot sites in the USA and China (Montross et al. 1994; Liu et al. 1994). Clearly, the concurrent-flow dryers operate at the highest temperature, the crossflow dryers at the lowest temperature. The disparity in operating temperatures between those measured in the USA and China is due to the different heat sources used in the two countries: natural gas in the USA, coal in China.

<table>
<thead>
<tr>
<th>Dryer type</th>
<th>USA (°C)</th>
<th>China (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concurrent-flow</td>
<td>205–290</td>
<td>150–160</td>
</tr>
<tr>
<td>Mixed-flow</td>
<td>130–140</td>
<td>120–150</td>
</tr>
<tr>
<td>Crossflow</td>
<td>85–120</td>
<td>90–120</td>
</tr>
<tr>
<td>Steam dryer</td>
<td>—</td>
<td>130–140</td>
</tr>
</tbody>
</table>

The grain-kernel temperature, not the drying-air temperatures, determines the drying rate of the grain in a dryer. Figure 2 shows the distribution of the kernel temperature in the crossflow, concurrent-flow, mixed-flow, and counterflow dryers. The variation in temperature (and in moisture content) between the kernels in the crossflow dryer is large, in the mixed-flow dryer relatively small, and in the concurrent/counterflow dryer non-existent. Also, in the crossflow dryer the grain kernels are subjected to the high inlet-air temperature for a period of hours, in the mixed-flow dryer for minutes, and in the concurrent-flow dryer for (only) seconds. Therefore, there are different high-level limitations on the drying-air temperature in the three dryer types.

Maize quality

The authors have recently investigated the effect of dryer type on maize quality (Montross et al. 1994; Liu et al. 1994). In the USA, three dryer types were tested, i.e crossflow, concurrent-flow and mixed-flow models. In China, the same three types were investigated, along with steam-drying and sun-drying installations. Tables 6 and 7 show the results of both studies.
Several conclusions can be drawn from the data in Tables 6 and 7:

1. Sun drying is able to produce maize with a minimum number of stress cracks if properly implemented.

2. Steam-dried maize usually has only a small number of stress cracks.

3. Of the three major high-temperature dryer types, concurrent-flow dryers cause the smallest increase in the number of stress cracks in maize kernels while crossflow dryers generate the largest increase.

4. Mixed-flow dryers fall between the concurrent-flow and crossflow dryer types with respect to the stress-cracking of maize.

Comparing the data in Tables 6 and 7 shows that the number of stress cracks recorded for the three major dryer types in China is lower than in the USA. This could be due to variety differences but is likely to be caused by the higher drying temperatures used in the USA than in China, i.e., concurrent-flow dryers usually operate at 250–275°C in the USA, but at 125–150°C in China.

A comparison between four dryer types is given in Table 8 with respect to the drying-air temperature, the maximum temperature reached by the grain, and the expected increase in stress-cracked kernels, in drying maize by ten percentage points of moisture.

**Dryer rating**

High-temperature dryers are usually rated for capacity only. In some cases the energy efficiency is given. A buyer has difficulty interpreting the dryer manufacturer's data due to the lack of a standard rating scheme.

The International Standards Organization (ISO) has proposed the standard 'Agricultural Grain Dryers—Determination of Drying Performance.' Until this standard has been approved, and accepted worldwide by grain-dryer manufacturers, it is impossible to draw objective conclusions from a comparison of different dryer types and dryer models.

**Dryer Control**

The moisture content of wet grain reaching a high-temperature continuous-flow dryer over a 24-hour period can vary greatly. This is due to the different harvest-procedure preferences, soil types, and variety selections of individual farmers. At commercial elevators it is not unusual to encounter moisture content differences of 10–15% in lots of maize received from different growers. Yet all the grain must be dried to approximately the same average moisture content. The challenge presented to the dryer operator, or the automatic controller, is to properly vary the speed of the unload auger and thus the residence time of the grain in the dryer.

Manual control of continuous-flow dryers often leads to significant overdrying or underdrying. Automatic control of continuous-flow dryers is usually designed to minimise these occurrences. Secondary objectives are minimising energy consumption and optimising dryer capacity, both necessarily subject to grain quality constraints (Eltigani and Bakker-Arkema 1987).
Table 6. Average type of stress cracks, stress-cracked percentage and stress-crack index of maize dried in three dryer types in the USA.

<table>
<thead>
<tr>
<th>Dryer type</th>
<th>None (%)</th>
<th>Single (%)</th>
<th>Multiple (%)</th>
<th>Checked (%)</th>
<th>Stress-cracked (%)</th>
<th>SCIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-stage concurrent-flow</td>
<td>47.4</td>
<td>5.8</td>
<td>27.1</td>
<td>19.7</td>
<td>52.6</td>
<td>185.6</td>
</tr>
<tr>
<td>Mixed-flow</td>
<td>34.5</td>
<td>8.0</td>
<td>32.5</td>
<td>25.0</td>
<td>65.5</td>
<td>230.5</td>
</tr>
<tr>
<td>Crossflow</td>
<td>12.2</td>
<td>3.4</td>
<td>38.6</td>
<td>45.8</td>
<td>87.8</td>
<td>348.3</td>
</tr>
</tbody>
</table>

SCIA = 1*(% single) + 3*(% multiple) + 5*(% checked) (Gunasekaran et al. 1985).

Table 7. Average type of stress cracks, stress-cracked percentage and stress-crack index of maize dried in five dryer types in China.

<table>
<thead>
<tr>
<th>Dryer type</th>
<th>None (%)</th>
<th>Single (%)</th>
<th>Multiple (%)</th>
<th>Checked (%)</th>
<th>Stress-cracked (%)</th>
<th>SCIA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concurrent-flow/crossflow</td>
<td>71.6</td>
<td>10.0</td>
<td>14.7</td>
<td>1.0</td>
<td>28.4</td>
<td>72.6</td>
</tr>
<tr>
<td>Mixed-flow</td>
<td>70.7</td>
<td>11.0</td>
<td>15.7</td>
<td>0.7</td>
<td>29.3</td>
<td>70.9</td>
</tr>
<tr>
<td>Crossflow</td>
<td>55.5</td>
<td>15.7</td>
<td>21.6</td>
<td>9.2</td>
<td>44.5</td>
<td>107.6</td>
</tr>
<tr>
<td>Steam</td>
<td>89.7</td>
<td>6.3</td>
<td>1.0</td>
<td>3.0</td>
<td>10.3</td>
<td>24.3</td>
</tr>
<tr>
<td>Sundrying</td>
<td>93.3</td>
<td>3.5</td>
<td>1.5</td>
<td>0</td>
<td>6.7</td>
<td>16.4</td>
</tr>
</tbody>
</table>

SCIA = 1*(% single) + 3*(% multiple) + 5*(% checked) (Gunasekaran et al. 1985).

Table 8. The average effect of dryer type on the drying-air temperature, the maximum grain temperature, and the percentage of stress-cracked kernels in maize.

<table>
<thead>
<tr>
<th>Dryer type</th>
<th>Drying air temperature (°C)</th>
<th>Maximum grain temperature (°C)</th>
<th>Stress-cracked kernels (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crossflow</td>
<td>80–110</td>
<td>80–110</td>
<td>70–85</td>
</tr>
<tr>
<td>Mixed-flow</td>
<td>100–130</td>
<td>70–100</td>
<td>40–55</td>
</tr>
<tr>
<td>Concurrent-flow</td>
<td>200–285</td>
<td>60–80</td>
<td>30–45</td>
</tr>
<tr>
<td>Steam</td>
<td>Ambient</td>
<td>40–50</td>
<td>10–20</td>
</tr>
</tbody>
</table>

Continuous-flow dryer control is of the classical or the adaptive type. Either the exhaust-air temperature or the inlet and outlet moisture contents of the grain are measured, and the speed of the metering roles is adjusted according to a specific control law. Temperature-based controllers are adequate for small inlet moisture variations; moisture-based control is recommended for large swings in moisture content.

A classical feedback controller reacts slowly when the residence time of the grain in the dryer is long. An optimal feedback control system requires a well-defined objective function, which is difficult to obtain mathematically. A classical feed-forward controller needs an accurate dynamic model of the drying process, which requires long computation time for on-line calculations (Marchant 1985).

An adaptive controller has been shown to offer the best technique for adequately controlling continuous-flow grain drying (Moreira 1989). Adaptive feedback and feed-forward control is able to minimise the fluctuation of the outlet moisture content even for large variations in the inlet and ambient conditions.

Fuzzy or expert control is used when the objective function is difficult to express mathematically. It employs a set of heuristic rules based on experimental knowledge and operator expertise (Zhang et al. 1990).

Two quality-control measures have been proposed to evaluate different control performances. One is based on the standard deviation of the grain moisture content and the other on the percentage of off-specification product. By employing these control measures, the success or the failure of a particular controller type can be quantified.

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Considerable computing power is required for continuous-flow dryer controllers. The required continuous or intermittent sensing of the grain moisture needs sophisticated instrumentation. Therefore, the cost of a control system for a continuous-flow grain dryer is relatively high.

Notwithstanding the substantial costs, dryer control systems are economically justified on many grain dryers.

**Dryer Economics**

The analysis of profitability of the purchase of a particular dryer is an essential part of the evaluation of different dryer types. Analyses commonly used, such as the payback period and rate of return, do not adequately express the economics in the dryer-selection process. The capital-budgeting (also called life-cycle costing) analysis does allow the buyer to analyse the cash-flows over time resulting from the purchase of a specific dryer model. The capital-budgeting procedure requires values of a series of parameters—including the fixed and operating costs, the energy consumption, the grain quality change, the fuel and maintenance costs, the service life, the time value of money (i.e. the interest to be paid on the loan), and so forth.

The capital-budgeting analysis provides a realistic comparison of dryer types. For instance, the initially costly dryer may in the long run be the better buy because it may produce better quality grain at lower operating costs and lower environmental pollution. A payback-period analysis may not reveal these advantages; a capital-budgeting analysis, spanning a 3–10 year planning horizon, will.

A capital-budgeting analysis of the purchase of a dryer requires knowledge, or accurate estimates, of a number of dryer-related parameters such as the dryer capacity, energy efficiency, salvage value, etc. Many of these parameter values are inadequately known, and thus have to be researched by engineers and economists.

As an example, the capital-budgeting costs of adding a grain-preheater to an existing concurrent-flow dryer are analysed (Montross 1995). [The preheater increases the capacity of high-temperature dryers by 10–15%.] The parameters used in the analysis are listed in Table 9. The drying costs in the table refer to the drying charges at a local grain elevator, and would be incurred if no preheater had been installed.

Table 9 shows the tonnage to be dried and the number of drying-operations to be required for the net present value (NPV) to be zero at a variable tax rate.

A capital-budgeting analysis of a high-temperature dryer provides quick answers to the effect on the net present value of: (1) the discount rate, (2) the fuel-inflation rate, (3) the loan policy, (4) the local drying cost, (5) the grain-quality premium and (6) the dryer energy-efficiency. In short, a capital-budgeting analysis provides for better economic information on a dryer, or on the add-on to a dryer, than can be obtained from an initial-cost or payback-period comparison.
References


In-store Drying and Grain Psychrometries

Robert Driscoll*

Abstract

Product drying, though conceptually simple, is the least understood postharvest operation. Successful drying produces a safe product, but drying problems can cause massive quality and actual losses. The interaction of a product with air can be represented on a psychrometric chart, a basic tool of the drying engineer, and this allows estimates of drying performance to be made. Interaction of the product with the air also will affect its chemical structure, microbial flora, and storage stability. A current trend in dryer models research is towards quality models which can be incorporated in deterministic models of grain drying, and are conveniently expressed in terms of the temperature and moisture histories of the product. Such models allow predictions of safe and optimal drying from simulated or historical weather data, as well as development of appropriate control algorithms. The trend in Southeast Asia is towards mechanisation and increased collection of grain in bulk, allowing technologies on a more efficient scale to be introduced.

Drying is one of the most common and least understood postharvest operations. Banga and Singh (1994) stated that drying is too complex to fully analyse in a rigorous mathematical sense, and that dryer design still mainly depends on experimental data. Although true, the application of basic science to situations such as drying of agricultural crops has led to a revolution in our understanding of drying equipment and strategies, but that revolution is only now starting to impact on the massive postharvest grain drying problem of Southeast Asia.

Grain drying in Southeast Asia

The wet season harvests originated through the development of high yielding, fertiliser-dependent varieties of grain. Hybrid varieties, due to their greater initial vigour, have helped to increase yields at a time when land, labour, and water are decreasing (Virmani and Dedolph 1994), and so have increased pressure on the postharvest system. Drying the grain became a major problem in the region, as sun drying proved insufficient for wet season tropical climates.

Thus, mechanical dryers have been investigated as an alternative. New types of dryers are now being developed at a great rate; for example, spouted and fluidised-bed dryers, and conduction drum dryers (Noomhorm et al. 1994). Soponronnarit and Prachayawarakorn (1993) have developed fluidised bed dryers for first stage drying of paddy, predicting a cost of about US$80 per tonne water evaporated, and studying energy, quality and throughput rates of the fluidised-bed drying system. This has now been commercialised in Thailand.

I worked on the dryer for the model grain depot at Jilin in China (Newman 1992), and so was able to observe developments there. China shows a slow trend towards mechanisation, the main delay being that the displaced labour force does not attract competitive wages compared with agricultural employment, which is currently 70% of employment. As the Chinese GNP rises, this trend towards urban society and 10% rural work force will accelerate (Schrock 1994). But all countries in Southeast Asia reflect this trend.

Interaction of grain with air

Drying inhibits product degradation by control of water activity only. Water activity determines the rates of most biological and chemical reactions of relevance to food systems. Thus, the design objective in drying is not to control moisture but to control water activity. Yet most dryer objectives are stated in terms of moisture.

The most common technique for dehydration is to allow interaction between low moisture air and the product, moisture being transferred to the air and then carried out of the grain mass in solution.
Other interactions between the grain and the air occur, many related to quality. A secondary interaction is a thermal interaction between the air and the grain, often referred to under constant aeration conditions as the initial transient. Some related effects are:

• Grain can be preserved cheaply by cooling (Barth 1993), giving independence of weather conditions and dryer delays, and at a low cost as cooling fronts propagate rapidly through a grain mass. Few have attempted to simulate more than the immediate dryer, with the exception of Chung et al. (1991), who simulated an on-farm grain storage system for American conditions, finding that gas-modulated burners gave a potential saving over on/off burner control. Recirculation of air was also studied in this simulation. My own work in simulating Malaysian mills as a drying system demonstrated dramatically the quality benefits that would result from cooling grain in an aeration bin at receival, so that the effect of dryer delays or bottlenecks within the complex would be alleviated. A reduction of dry matter loss from 0.8 to 0.5% was observed using typical harvest data, this being the difference between accepting and rejecting the grain for export. The cost would have been that of a receival bin (bulk), aeration equipment and a small fan. No cooling system was required.

• Grain kept in bags absorbs moisture at a rate of about 0.5% per month in tropical climates (Guritno et al. 1991).

• If grain is sealed inside a plastic bag, gases build up due to respiration which are self-limiting, allowing long term storage (several months) by this simple technique (Kawashima and Siriacha 1990).

Relevance of isotherms

Drying is a two-phase dual component system. The two phases are vapour and liquid, and the two components are water and water vapour. At equilibrium, the number of degrees of freedom *F* is:

\[
F = 2 \text{ (phases)} - 2 \text{ (components)} + 2 = 2
\]

Since we have two degrees of freedom, if we define two state variables of the system we have defined the system state precisely. Choosing relative humidity (RH) and temperature (T) as our state variables, we can then write:

\[
M = f(T, RH)
\]

where *f* is a function, and *M* is the dry basis moisture content. For a particular temperature, the relation between *M* and RH is called an isotherm, and is product dependent. In turn, relative humidity is defined as a partial pressure ratio:

\[
RH = \frac{p_v}{p_s}
\]

where *p_v* is the vapour pressure exerted by moisture in the air, and *p_s* is the vapour pressure of moisture in saturated air at the same temperature. This definition identifies RH with water activity *a_w*, although relative humidity is generally expressed as a percentage whereas water activity never is.

Recent research has suggested that there are criteria other than water activity and temperature which determine reaction rates, and these alternatives will be discussed briefly in a later section.

The result of the above identification is that we can plot lines of constant moisture (isosteres) on a psychrometric chart, by holding moisture constant and using the function *f* to calculate the relative humidity as temperature varies. For most agricultural products, temperature has less effect than moisture on the relative humidity, so that the isosteres tend to follow the relative humidity lines. This accounts for the use of moisture content for a particular product as the commercial determinant of the end point of drying.

Work has continued internationally on building up a comprehensive library of product properties, with individual researchers continuing to collect basic thermophysical data.

### Psychrometrics

#### Definitions

Air is used as the transport medium for moisture in the dryer. So as far as the dryer is concerned, air is a two component mixture of a gas (primarily O₂ and N₂) and a vapour (water). A limited volume of air above a free water surface becomes saturated, the amount of moisture present in the air depending on the temperature only, and independent of the pressure of the dry air. Relative humidity is a measure of the proportion of vapour present to the maximum amount the air can hold (at saturation). Absolute humidity is the mass of moisture in the air relative to the mass of the gas component of the air (called dry basis). Plots of air state variables are called psychrometric charts (Fig. 1), of which the most important is a plot of temperature against absolute humidity.

The example chart shown also demonstrates relative humidity lines, enthalpy lines, and density lines. All of these are important in grain drying. Air enthalpy is a measure of the heat content of the air and its contained vapour:

\[
h = m_a [c_a T + H (c_v T + \lambda_0)]
\]

where *h* is the air enthalpy (kJ), *m_a* is the mass flow rate of the air on a dry basis (gas component only), *c_a* and *c_v* are specific heats of the air and water vapour, respectively, (kJ/kg·K) and \(\lambda_0\) is the latent heat of water at 0°C.
Enthalpy is important in drying because for an adiabatic, constant pressure system, enthalpy is conserved. Many dryers approximate this situation. Thus on our psychrometric chart, drying can be represented using lines of constant enthalpy. In general, the inlet air will start at a different enthalpy from the initial product, and thus for the product to come to equilibrium with the air, two balances are required: a moisture balance and a thermal or enthalpy balance. In general, thermal balances occur quickly (typically more than 30 times faster than moisture balances).

**Drying on a psychrometric chart**

Thin-layer drying of a product can be represented on a psychrometric chart using this information. First the product (P) and inlet air (A) points are plotted (Fig. 2). If the product is high in moisture, the product point will be close to the 100% relative humidity (saturation) line. Construct a line from the air point along its enthalpy line to intersect the 100% saturation line. Construct a second line at constant moisture from the initial product state to intersect the air enthalpy line, and call this point B. The line PB represents the enthalpy 'front' moving across the product, while the line BA represents the product drying.

This graphical method is a good way of explaining the drying process, but is not as accurate as an equation-based solution method. In practice there is some moisture change in the product in the enthalpy front and some change in enthalpy in the moisture front for both the air and the product. These changes are generally small enough to be neglected.

Many researchers have developed models of thin-layer drying. Some recent work is that of:
- Parti (1990), who studied diffusion with a temperature and moisture-dependent diffusion coefficient;
- Bala and Woods (1992), who combined internal diffusion with surface evaporation for malt;
- Were and Jayas (1994), who in a recent evaluation comparing a range of popular models found that the two-term exponential model was superior for describing the thin-layer drying rate of maize;
- Martinez-Vera et al. (1995), who developed a thin-layer drying model of corn based on diffusion, using finite element analysis.

Extension of this concept to deep bed dryers is discussed in the next section.

**Other types of dryers**

Practically all dryers are systems for interacting air with the product. Although only in-store dryers were considered, the principles can be extended. Some examples showing specific aspects of grain/air interaction are given below.

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**Psychrometric Chart**

for humid air @ 101325.6 pascals absolute.


Psychrometric data.
Saturation Curve: Wexer 1976 (eq 16a).
Wet bulb: Smithsonian Met. Tables 1963 (Ferrel eq).

![Psychrometric Chart](image)

**Figure 1.** An example of a psychrometric chart (courtesy James Darby, Stored Grain Research Laboratory, CSIRO Division of Entomology, Canberra).
Figure 2. Graphical representation of grain drying on a psychrometric chart. See text for explanation.

One aspect of air properties of great interest in dryer design is solar energy, which can be used to partially heat the air and so dry the grain (Oosthuizen 1992). Although technically possible and achieved by, for example, Somchart Soponronnarit in ACIAR Project 8308, it has not proven to be a commercially successful approach.

Spouted-bed dryer dynamics are complex, especially when it comes to scale up, and hence simplified arrangements are being tested such as two-dimensional spouted beds (Kalwar and Raghaven 1993). Both spouted-bed and fluidised-bed dryers use high airflow rates to fluidise all (or a part) of the granular product mass, allowing rapid heat transfer.

In-store drying

A deep bed of product can be represented as a number of thin layers superimposed, and so can also be represented by points A, B, and P on a psychrometric chart. The first layer acts as a true thin layer for constant inlet conditions. The second layer is affected by the outlet conditions of the first layer, resulting in a time delay before it is exposed to drying air. In this way, there will be a time delay dependent on depth in the bed before layers deep within the grain will be exposed to the same conditions as the first layer.

Thus, two fronts are generated for constant inlet conditions to a deep bed of material. The first is an enthalpy front, generated at the air inlet and propagating relatively rapidly through the grain mass. The second front is the moisture front, which is a drying front. In predicting the rate of moisture removal, the difference between the absolute humidities of the air inlet and zone B conditions determines the rate of drying.

The advantage of drying a deep bed rather than a thin layer is that the drying air is exposed to a large amount of product, and so has more time to come to equilibrium with the product. The wettest product is at the air exit. This gives high moisture efficiency without the need to recirculate the air or stir the grain. In contrast, thin-layer dryers give limited time for contact between the air and the product, so that the air leaves the product with unused moisture capacity.

Deep-bed drying has been modelled extensively over the past three decades. In a recent review of theories (Cenkowski et al. 1993), only three types of drying models were recognised: the equilibrium, non-equilibrium, and logarithmic. In practice this classification neglects by far the most successful model, the so-called near-equilibrium model, which is actually the assumption of thermal equilibrium without also assuming moisture equilibrium. At low temperatures, near equilibrium models were found to
The drying time can be estimated by equating the moisture removal rate with the amount of moisture in the bed above equilibrium (Bowrey and Driscoll 1986).

Work to develop and improve models of deep-bed drying continues, for example, on:

- optimising integration step size—the work of Jin-dal and Siebenmorgen (1994) on the importance of the mass ratio of grain to air in a control volume;
- respiration—the heat and water generated by respiration were found to have a significant effect on drying predictions for a deep bed (Soponronnarit and Chinsakolthanakorn 1990), with heat increasing the drying rate and the moisture produced retarding it;
- volume shrinkage—an example of a real bed effect is volume shrinkage, for many years not included in dryer models as being too difficult. Work on collecting empirical data on bed shrinkage is rare. An example is Lang and Sokhansanj (1993) for wheat and canola;
- complexity—some aeration models are of great complexity, covering three-dimensional flow using volume averaging theory. Van Graver (1992) reviews work by Thorpe, Wilson, and others. The main problems with deep bed drying are:
  - creation of a moisture gradient between the top of the bed and the inlet;
  - lost opportunity cost, as product is held up in the dryer for long periods, so tying up capital;
  - compaction of lower layers at high moistures, resulting in increased pressure drop, higher costs and slower drying rates; and
  - loading and unloading times are comparatively long.

The main advantages are:

- reduced quality deterioration;
- low energy costs for drying under the right conditions; and
- reduced grain losses.

**Psychrometrics and quality**

There are three parameters for assessing any process equipment: cost of operation (including capital and equipment costs), throughput, and product quality. In this section quality is considered. Dryer models need to include quality models to allow the model to be used for strategy development. For example, in the in-store drying model developed by the University of New South Wales (Szczenicki and Driscoll 1995), four quality models are included, dry matter loss, ergosterol increase, yellowing and seed viability. In most cases, it is the interaction of the product with its psychrometric environment which causes changes in quality.

Recent studies of microflora in milled grain samples of rice from Southeast Asia have shown a predominance of field fungi, with few observations of storage fungi (Pitt et al. 1994), indicating that the milling process removes most of the microflora.

Great progress in dryer design has been achieved with the discovery that fluidised-bed drying of paddy does not necessarily result in poor quality grain, and that fact, coupled with the ability to economically recirculate the air inside a fluidised-bed dryer has led to a rebirth of this technology in southeast Asia (Ghaly et al. 1984; Tumambing 1992; Magampon and Elefrano 1993). This success was due to the discovery that high temperature drying does not damage grain provided that the grain is initially at a high moisture content (Tallada et al. 1994). Rather it is the steepness of the moisture gradient within the grain which correlates to head rice yield (Siebenmorgen 1992), with the greatest reduction occurring during the first 8 hours of exposure to an adsorption environment.

The results have come from studies on causes of fissuring and breakage during milling of rice. Reduction in head rice yield is caused by moisture readesorption (Banaszek and Siebenmorgen 1990). Although Japanese researchers in the 1930s had established that fissure generation is due to adsorption rather than drying, this information was not disseminated until rediscovered by Kunze over a long series of careful experiments (see Kunze 1991). This has resulted in major rethinking of drying methodologies, with the result that grains are now frequently dried under much harsher conditions, yet with less loss of quality.

More generally, Siebenmorgen (1992) confirmed that moisture reduction gradients caused fissuring, the majority of fissuring occurring during the first 8 hours after exposure to an adsorption environment. This suggested that maize could be dried using high temperatures and high relative humidities ( Estrada and Litchfield 1993).

More detailed research on moisture distributions led to the disturbing discovery that individual rice grains vary widely in moisture content with their growth stage, and that even position on the panicle can have extreme effects. Did this matter? Unfortunately, the answer is yes. High moisture rice releases its moisture to low moisture rice, causing that rice to fissure, and hence reducing head rice yield (Siebenmorgen et al. 1992).

We have come to understand more about the chemistry of grain drying as well; for example, the effects on nutrients (Barrier-Guijlot et al. 1993), enzymes (Chrstisl 1990, 1993), and the location and causes of fissuring in the grain structure (Juliano et al. 1993; Juliano and Perez 1993; Peplinski et al. 1994). Theoretical calculations of fissure development have been
attempted by several researchers, one of the most successful being a finite element approach for maize and soybeans by Irudayara et al. (1993), using van Mises' failure criterion, and including thermal and moisture expansion effects and a viscoelastic model of the internal grain structure. Their model predicted fissuring at high temperatures (>70°C), due to stresses of the order of 20 atmospheres being generated near the grain surface.

Thus, we seem to have come full circle, with fissuring due to drying, not reabsorption, being indicated by the models. Studies at the University of New South Wales, on moisture gradients in rice grains (Driscoll et al. 1990) suggested that the gradients during drying are not as steep as the gradients that are created by exposure of a dried grain to a humid environment. This suggests that most fissuring could be prevented by controlling the relative humidity of the air to which the grain is exposed after drying to below 40%, until moisture diffusion within the grain has allowed re-equilibration to occur (at least 2 hours for paddy).

Other important quality models include the following:

- A storage quality indicator developed for wheat and rice was yellowing, which is discoloration during storage due to long-term chemical reactions (Bason et al. 1990).
- Several models exist for seed viability [e.g. Giner et al. (1991), for wheat].
- Pinto et al. (1991) and Gibson et al. (1994) have modelled aflatoxin production in terms of water activity and temperature.
- Evranaz (1993) has modelled oxidation of fats in peanuts, expressing it as a function of temperature and moisture.
- Many grain storage pests were found to be dependent on wet-bulb temperature [Desmarchelier (1988) with species of beetles]. Other researchers found that this was not always true [Beckett et al. (1994), with insect pests].
- Psychrometries and dryer control

Control of a grain store, whether for drying or aeration, depends critically on the interaction between the product and the air. Criteria for an aeration control system are that it should be accurate, quick to react, stable, and tolerant of changes. Specific points to consider in aeration control are (Moreira and Bakker-Arkema 1992):

- prevention of overdrying is a major concern;
- feedback and adaptive feedforward can be successfully applied, and a recent work even combines these two approaches;

- there is a wide choice for control objectives, for example, uniform drying, safety, lowest cost in one year, lowest cost over 20 years, maximum throughput, etc.;
- there is always a trade-off with deep-bed drying between reduced costs and increased dry matter loss.

In a detailed study of control and aeration strategies for near ambient systems for Canadian wheat, Ryniecki (1991) analysed humidistat control, time clock, varying airflow rates, and burner strategies using a stochastic (probability) model of weather and drying. The drying model was based on Parti's formulation (Parti 1990) of the differential drying rate across a layer, converted to stochastic form by expressing temperature in the equation as a randomly fluctuating variable linked to weather conditions (Ryniecki et al. 1993; Ryniecki and Jayas 1992). This allows a probabilistic analysis of 20 years of weather data so that strategies which both guarantee and optimise aeration could be developed.

They found that varying the airflow rate and controlling the relative humidity by air selection worked best with time-varying humidity limits, where the band of acceptable air was increased if weather conditions continue unfavourable, to ensure enough hours of aeration (Ryniecki et al. 1993). This uses the same principle as the Australian CSIRO's proportional controller, a mechanical device for ensuring sufficient aeration hours.

Banga and Singh (1994) have also developed a technique for optimising aeration conditions, based on optimal control theory. What is especially interesting about their work is that instead of optimising from the perspective of achievement of technical goals (such as least cost, final moisture), they have also optimised on quality, including maximum nutrient/ enzyme retention, minimum process time, and maximum energy efficiency as their control objectives. This emphasis on final product quality is a growing trend in grain storage research.

A further advance in modelling has been through the association of expert systems with dryer models (Kawamoto et al. 1992). In this case a simulation of harvest moistures based on weather data is coupled with an expert system which predicts likely pest outbreaks and suggests solutions.

The area of aeration control is expanding rapidly as new techniques are developed for reducing the major cost of drying of grains. This is possible through psychrometries.

Conclusions

Three points should be emphasised.

We have not yet reached the stage where a mechanical dryer is the only solution. In most areas
in Southeast Asia, sun drying is the preferred option, not just for the sake of tradition but in terms of pure economics.

As Asian countries move towards increased GNP and a resulting increased wage level, the trend will be away from rural employment towards mechanisation, and the current research on dryer design, control, and optimisation will bear increasing fruit.

Reducing costs and optimising dryer performance depends heavily on operators understanding their product and its interaction with air. This is the realm of psychrometry. High-temperature dryers are less dependent on operator skills, at the cost of reduced thermal efficiency at low moisture contents, whilst near ambient systems such as in-store dryers are heavily dependent on operator skills. For a large scale drying complex, massive savings are possible through a deeper understanding of the drying process, for example, cooling the grain at receival, two-stage drying, and prevention of drying delays.

References


Kawashima, K. and Siricha, P. 1990. Prevention of aflatoxin contamination in maize grains with high moisture
content by using plastic bags. TARC Research High­
ights, 13–15.
technology: a review with emphasis on rice. Transac­
tions of the American Society of Agricultural Engineers,
7, 717–723.
Lang, W. and Sokhansanj, S. 1993. Bulk volume shrinkage
during drying of wheat and canola. Food Process Engi­
neering, 16, 305–314.
Magampon, M.T.e. and Elepano, A.R. 1993. A laboratory
study of fluidized bed drying of high moisture paddy.
Philippine Agricultural Mechanization Bulletin, 1, 15–19.
Martinez-Vera, C., Vizcarrar-Mendoza, O., Galan-Domingo,
air grain drying modelling and validation. Drying Tech­
application in grain drying simulation. In: Naewbany,
J.O. and Mamlay, A.A. Proceedings of the 14th ASEAN
Technical Seminar on Grain Post-Harvest Technology,
depot. World Grain, 10, 17–18.
Design and development of a conduction drier for accel­
Oosthuizen, P.H. 1992. The selection of simple indirect
solar rice dryers. Proceedings of the 8th International
Drying Symposium, Montreal, 1992, 1465–1474.
Parry, J.L. 1985. Mathematical modelling and computer
simulation of heat and mass transfer in agricultural grain
drying: a review. Journal of Agricultural Engineering, 32,
1–29.
Patti, M. 1990. A theoretical model for thin-layer grain dry­
ing. Drying Technology, 8, 101–113.
1994. Drying of high-moisture corn: changes for accel­
Influence of water activity, temperature and incubation
time on the accumulation of aflatoxin B1 in soybeans.
Food Microbiology, 8, 195–201.
Pitt, J.L., Hocking, A.D., Bhudhasamai, K., Miscamble,
mal mycoflora of commodities from Thailand. 2. Beans,
rice, small grains and other commodities. International
Journal of Food Microbiology, 23, 35–53.
Ryniecki, A. 1991. Control systems for near-ambient grain
drying. In: Cereal grain – mycotoxins, fungi and quality
Ryniecki, A. and Jayas, D.S. 1992. Stochastic modeling of
grain temperature in near-ambient drying. Drying Tech­
nology, 10, 123–137.
ized control-strategy for near-ambient drying of wheat
under Canadian-prairie climate. Transactions of the American Society of Agricultural Engineers, 36, 1175–
1183.
Schrock, M.D. 1994. Grain harvesting in China as an exam­
ple of the mechanization process. Agricultural Mechani­
zation in Asia, Africa and Latin America, 25, 54–60.
Siebenmorgen, T.J. 1992. Relating moisture transfer rate in
rice to kernel quality. Proceedings of the 8th International
Drying Symposium, Montreal, 1992, 58–73.
of heat and water from respiration on drying rate and
energy consumption. ASEAN Journal on Science and
taining quality, maximizing throughput and minimizing
energy consumption in fluidized bed paddy drying. In:
Naewbany, J.O. ed. State of the art of the grain industry
in ASEAN: a focus on grain handling and processing.
Proceedings of the 15th ASEAN Technical Seminar on
Grain Post-Harvest Technology, Singapore, 8–11 Sep­
Szefnicki, G.S. and Driscoll, R.H. 1995. In-store drying and
quality maintenance in grain. In: Champ, B.R. and High­
ley, E., ed., Postharvest technology for agricultural prod­
ucts in Vietnam. ACIAR Proceedings, No. 60, 42–49.
effects of high temperature drying on rice milling quality.
Paper presented at the PSAE Annual Convention, Manila
masters thesis, University of New South Wales, Aus­
tralia.
Virmani, S.S. and Dedolph, C. 1994. Reaping the benefits of
Weres, J. and Jayas, D.S. 1994. Thin-layer drying of corn:
experimental validation of a new numerical structural
Design of Aeration and Drying Systems
Design Parameters for Aeration and In-store Drying Systems

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Abstract

This paper summarises some of the main engineering considerations and parameters for the design of aeration and in-store drying systems.

Both aeration and in-store dryers operate on the principle of forcing ambient air through a mass of stored grain and, in many respects, the engineering design principles are much the same. Drying simply requires a larger volume of air, and in some cases the addition of some low-temperature heat.

The paper covers the main aspects of designing systems for moving air through grain, most of which have been well documented in the past. The paper covers methods for determining:

- the fan operation time fraction;
- specific airflow rates for aeration and drying;
- selection of airflow direction;
- selection of air-duct distribution pattern;
- airflow resistance in ducts;
- airflow resistance in grain;
- selection of fans.

The paper presents some new ideas for aeration of large volume 'squat' silos, but generally offers a guide to designers based on well known practices and past experience.

In-store drying and aeration both involve forcing ambient (or near ambient) air through a grain mass.

It is well known that the forced movement of air through grain sets up both temperature and moisture fronts which move through the grain in the direction of the airflow—the temperature front moving very much faster than the moisture front. Thus, grain aeration is likely to result in some moisture change, and in-store drying will cause changes in grain temperature.

However, while similar in principle, the two practices have very different aims:

- In-store drying is carried out on relatively high moisture grain, and its purpose is to remove moisture from the grain to make it 'safe' for storage before fungal activity begins. Temperature control is a secondary consideration, except in high humidity conditions when it may be necessary to increase the air temperature with supplementary heat to reduce its relative humidity to a level where it will remove moisture.
- Aeration is normally performed on relatively low moisture grain with the purpose of cooling the grain in order to preserve it by maintaining its 'condition'. Drying of grain is not a consideration when aerating, since the airflow rates are normally too low to have much influence on moisture content.

Cooling of grain by aeration significantly reduces insect population growth, mould growth, and loss of viability (or germination potential). In addition, aeration can prevent the occurrence of temperature differentials within the grain which can lead to moisture migration; it can also inhibit the development of odours and grain discoloration.

This paper summarises the basic design parameters for in-store aeration and drying systems. The design of hot air continuous-flow dryers is beyond its scope.

From an engineering designer's point of view, aeration and in-store drying systems differ principally in the quantity of air that is required, and the possible addition of supplementary heating (for drying). Other engineering factors come into play when con-

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sidering some of the more sophisticated options for in-store drying, but the principal design parameters remain the same, and involve selection of:

- fan operation time fraction;
- specific airflow rate;
- airflow direction;
- air-duct distribution pattern;
- air-duct sizes; and
- fan or fans.

The selection of the specific airflow rate is the most significant of these design considerations. Compared with this, the selection of duct configuration, duct size, and fan type are relatively routine design matters. However, before the airflow rate is determined, it is important to select the fan operation time fraction.

**Fan Operation Time Fraction**

The fan operation time fraction is the percentage of time that fans operate when blowing air through a grain mass.

In the case of an in-store drying system, the need for controlling fan operation is relevant only when the grain moisture has reached a level that is close to equilibrium with the average daily relative humidity. In normal drying operations, the fans are run 100% of the time (even during periods of rain) in order to minimise the drying period.

In aeration systems, the fans are normally switched on and off for the purpose of selecting only the coolest air in order to reduce the temperature of the grain. Various control systems are used—including manual controls, fixed time settings, time proportional controls, and more sophisticated systems which monitor both air and grain temperature and/or relative humidity. Automated systems are far more efficient than manual ones, both in terms of minimising fan-hours and grain damage.

The most commonly used controller in Australia is the time-proportioning controller (developed by CSIRO), which automatically turns the fans on when ambient air temperatures go below a set point, and turns them off when it goes above it. The controller automatically adjusts the set-point to ensure that the fans operate for a set proportion of time. By reducing the proportion of time that an aeration system operates, the slower will be the rate of cooling of the grain (because less air is being used), but because it selects only the coldest air of the day, the controller ensures that the average temperature of the selected air will become lower as the aeration time fraction gets smaller. Hence, a time-proportioning controller has the effect of reducing the grain temperature as the time fraction is reduced.

Common practice (in Australia) is to select a fan operation time fraction of 50% for initial cooling of newly harvested grain (to speed up the cooling process), and to reduce this to 15% for 'maintaining' the grain and for further reducing its temperature, once the initial cooling has been achieved.

**Specific Airflow Rates**

**General**

The 'specific' airflow rate is the quantity of air passing through a grain mass divided by the volume of grain it passes through (e.g. measured in litres of air per second per tonne of grain, or m³/min/m³). Adjacent to an air duct (i.e. before the air passes through any grain) the specific airflow rate is infinitely large. As the air passes through the grain mass, the specific airflow rate becomes smaller and smaller, until it reaches a minimum value at the surface of the grain. It is this minimum value of specific flow rate that governs the cooling or drying performance of a system, since it defines the time that it takes for cooling and/or drying the grain mass.

Thus, the minimum specific airflow rate governs the speed of the 'temperature front' in the case of aeration, and the 'moisture front' in the case of grain drying. Estimating the speeds of both these fronts depends on a number of factors, the principal factors being—apart from the physical properties of the grain—the temperature and moisture of the grain and of the air being passed through it. Air temperature and moisture are highly variable factors, and the design engineer must often rely on the work of the research scientist to assist in determining the airflow rates applicable for aeration and in-store drying, especially in subtropical and tropical regions in which ambient conditions may often be only marginally useful for either purpose.

**Aeration**

Ideally, the airflow rate should be sufficient to allow cooling of a newly harvested grain mass within a period of about 4–5 weeks in temperate areas. The cooling period needs to be much less than this in subtropical and tropical areas unless the grain moisture is uniformly below an equilibrium relative humidity level of around 70%. A value for the cooling period can be estimated from equation (1) (from Hunter 1986):

\[ q = \frac{e}{GA\theta \rho} \]

where:
- \( q \) is the airflow rate in m³/kg/sec;
- \( e \) is the porosity of the grain bed (say 0.41 for wheat);
A is the cooling front velocity ratio (i.e., cooling front speed/interstitial air velocity) (say $0.75 \times 10^{-3}$ as a conservative figure); 
\( \theta \) is the desired cooling time (in seconds—say 3 \( \times 10^6 \) for five weeks); 
\( G \) is the flow distribution factor (say 0.8 for vertical storages and 0.5 for horizontal storages); 
\( f \) is the fan operation time fraction (say 50\% for initial cooling); and 
\( \rho \) is the bulk grain density.

The above equation may give airflow rates that are slightly lower than those commonly recommended. Airflow rates commonly recommended for cooling aeration vary according to the climatic conditions and storage type, and these are summarised in Table 1 (from Foster and Tuite 1982).

<table>
<thead>
<tr>
<th>Storage type</th>
<th>Temperate climate</th>
<th>Subtropical climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>0.8–1.6 L/sec/t</td>
<td>1.6–3.2 L/sec/t</td>
</tr>
<tr>
<td>Vertical</td>
<td>0.4–0.8 L/sec/t</td>
<td>0.8–1.6 L/sec/t</td>
</tr>
</tbody>
</table>

The need for higher rates in horizontal storages is to allow for the fact that air distribution is less uniform. Higher airflow rates are recommended for warmer subtropical climates to provide more rapid cooling during the short periods when air temperatures are low enough to be used for aeration.

Ambient aeration effectively brings the wet-bulb temperature of the grain into equilibrium with the wet-bulb temperature of the air. All the benefits achieved through cooling of the grain through aeration (viz. reduced insect activity, reduced moulding, etc.) are directly related to reduction in the wet-bulb temperature of the grain (or more specifically, the wet-bulb temperature of the interstitial air which is in equilibrium with the grain).

In order to evaluate the effectiveness of aeration on a grain mass, dry-bulb temperature readings of the grain should be taken regularly and converted to wet-bulb readings using a psychrometric chart or conversion tables (such as Table 2 which applies to wheat and maize). For optimum results, grain should (where possible) be cooled to around 10–15°C.

It should be clearly understood that the airflow rates which are useful for aeration of grain are quite insufficient to dry the grain other than to a very superficial extent. The benefits of aeration result only from the cooling of the grain and in equalising temperatures within the grain mass.

Drying

In the case of in-store drying, the critical requirement is not to preserve the condition of the grain, but to change its moisture content. The requirement is to dry it quickly enough that deterioration by moulding is prevented, and this may often require airflow rates 50 to 100 times those used for aeration.

The rate of moulding of grain is linked to its temperature and moisture content. Some species of moulds are active even at very low temperatures, and high moisture grain stored at or below freezing point may experience moulding if left long enough in storage. At high temperatures and high moisture, moulding takes place very quickly as can be seen from Table 3 (from Brooker et al. 1992).

The rate of drying—and hence the rate of airflow—must be such that the drying front passes through the grain mass before moulding starts.

The drying time can be roughly estimated from a heat balance equation such as equation (2) (from Brooker et al. 1992):

$$ t = \frac{v \cdot h_{fg} \cdot (DM) \cdot (M_o - M_e)}{60 \cdot c_a \cdot (T_a - T_g)} $$

where 
\( t \) = time (hours); 
\( n \) = specific volume of the moist air used for drying (m$^3$/kg); 
\( c_a \) = specific heat of dry air (J/kg·°C); 
\( (T_a - T_g) \) = dry bulb temperature drop through the grain mass; 
\( h_{fg} \) = heat of vaporisation at saturation (J/kg); 
\( DM \) = dry matter weight (kg); 
\( M_o \) = initial grain moisture level (%); 
\( M_e \) = equilibrium (final) grain moisture level (%); and 
\( Q \) = airflow rate (m$^3$/hour).

Table 4 offers designers some general guidance on minimum airflow rates for wheat and maize (based on U.S. experience) in order to achieve drying rates fast enough to avoid moulding in temperate climates.

Note that slightly increasing the temperature of the air by adding heat will increase the rate of drying. However, the recommended airflow rates should not be reduced to account for this, since the increased drying air temperature also increases the temperature of the moist grain above the drying front, and thereby increases the rate of mould development. The airflow rates in Table 4 are therefore recommended for both ambient air drying, and low temperature air drying.
Table 2. Tabulated values of equilibrium wet-bulb temperature for grain at varying moisture content.

<table>
<thead>
<tr>
<th>Dry bulb grain temp</th>
<th>5°C</th>
<th>10°C</th>
<th>15°C</th>
<th>20°C</th>
<th>25°C</th>
<th>30°C</th>
<th>35°C</th>
<th>40°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Wheat</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8%</td>
<td>3.7</td>
<td>6.5</td>
<td>9.6</td>
<td>12.3</td>
<td>15.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10%</td>
<td>2.5</td>
<td>7.2</td>
<td>11.0</td>
<td>15.2</td>
<td>19.5</td>
<td>24.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12%</td>
<td>1.0</td>
<td>6.0</td>
<td>10.2</td>
<td>14.7</td>
<td>19.0</td>
<td>24.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>14%</td>
<td>2.7</td>
<td>7.4</td>
<td>12.0</td>
<td>16.5</td>
<td>21.0</td>
<td>26.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>16%</td>
<td>3.8</td>
<td>8.5</td>
<td>13.0</td>
<td>18.0</td>
<td>22.5</td>
<td>27.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20%</td>
<td>4.9</td>
<td>9.8</td>
<td>14.6</td>
<td>19.3</td>
<td>24.0</td>
<td>29.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b) Maize</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8%</td>
<td>2.2</td>
<td>6.0</td>
<td>10.0</td>
<td>13.9</td>
<td>18.0</td>
<td>22.4</td>
<td>26.8</td>
<td></td>
</tr>
<tr>
<td>10%</td>
<td>-1.0</td>
<td>3.5</td>
<td>8.0</td>
<td>12.2</td>
<td>16.4</td>
<td>21.0</td>
<td>25.8</td>
<td>30.7</td>
</tr>
<tr>
<td>12%</td>
<td>0.8</td>
<td>5.3</td>
<td>9.8</td>
<td>14.6</td>
<td>19.2</td>
<td>23.9</td>
<td>29.0</td>
<td>33.2</td>
</tr>
<tr>
<td>14%</td>
<td>1.9</td>
<td>6.7</td>
<td>11.6</td>
<td>16.2</td>
<td>21.1</td>
<td>26.0</td>
<td>31.1</td>
<td></td>
</tr>
<tr>
<td>16%</td>
<td>2.8</td>
<td>7.9</td>
<td>12.8</td>
<td>17.7</td>
<td>22.5</td>
<td>27.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20%</td>
<td>4.0</td>
<td>9.1</td>
<td>14.2</td>
<td>18.8</td>
<td>23.8</td>
<td>28.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Storage life of maize.

<table>
<thead>
<tr>
<th>Maize temp (°C)</th>
<th>Storage life in days under aeration for varying maize moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15.5%</td>
</tr>
<tr>
<td>−1.1</td>
<td>2276</td>
</tr>
<tr>
<td>1.7</td>
<td>1517</td>
</tr>
<tr>
<td>4.4</td>
<td>1012</td>
</tr>
<tr>
<td>7.2</td>
<td>674</td>
</tr>
<tr>
<td>10.0</td>
<td>450</td>
</tr>
<tr>
<td>12.8</td>
<td>299</td>
</tr>
<tr>
<td>15.6</td>
<td>197</td>
</tr>
<tr>
<td>18.3</td>
<td>148</td>
</tr>
<tr>
<td>21.1</td>
<td>109</td>
</tr>
<tr>
<td>23.9</td>
<td>81</td>
</tr>
<tr>
<td>26.7</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 4. Minimum airflow rates for in-store drying in USA.

<table>
<thead>
<tr>
<th>Grain</th>
<th>Grain moisture (% wet basis)</th>
<th>Minimum airflow rate (m³/m³/min)</th>
<th>Minimum airflow rate (L/sec/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>20</td>
<td>2.4</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>1.6</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>0.8</td>
<td>10</td>
</tr>
<tr>
<td>Shelled maize</td>
<td>25</td>
<td>4.0</td>
<td>50</td>
</tr>
<tr>
<td>and grain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sorghum</td>
<td>20</td>
<td>2.4</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>1.6</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>0.8</td>
<td>10</td>
</tr>
</tbody>
</table>

Source: USDA (1965).
The figures in Table 4 are consistent with those recommended for in-store drying of rice in near-tropical conditions (such as in Southeast Asia) where it is recommended that minimum airflow rates of 1.5 m$^3$/m$^3$/min are adopted. In-store drying in such regions should not be attempted unless the initial grain moisture is not more than 18% and the grain bed depth is less than 4 m.

Direction of Airflow

Consideration of direction of airflow direction is more usually associated with aeration system design than with drying systems. In-store drying systems almost always involve upward movement of air through the grain. Aeration systems, on the other hand, can use either upward or downward airflow.

There are advantages and disadvantages in both alternatives and there seems to be no universal consensus as to which option is better in any given circumstance. The advantages and disadvantages of each are summarised below.

Upward airflow aeration

**Advantages**
- The compression of the air as it is blown into the bottom of a storage, results in a small rise in air temperature and thereby a reduction in the relative humidity of the air. A temperature rise of 3–4°C can remove the danger of increasing grain moisture content in high ambient relative humidity conditions. This can be particularly important in sub-tropical climates where the lowest temperatures are recorded at night when relative humidity can be close to 100%.
- In situations where warm grain may be added to a bin after aeration has begun, the use of upward aeration avoids the situation where air passes first through the warm grain, and thence downwards to warm the previously cooled grain underneath.
- In hot conditions, air may be warmed under a storage roof. Upward aeration blows this warm air out of the storage, rather than pulling it down through the grain mass.
- The last cooled layer of grain in the grain mass is the top surface layer, where grain temperature and moisture levels are easily checked.
- Upward airflow results in more uniform air distribution, particularly in flat stores.

**Disadvantages**
- In cool conditions, the top surface of a grain mass will cool naturally, as will the roof of the storage. Upward airflow through warmer grain may result in condensation of moisture in the cooler upper layer, or on the underside of the storage roof. [This can be minimised by installing a small fan in the storage roof.]
- Increase in grain moisture levels around the aeration duct can occur if the average relative humidity of the aeration air is above the equilibrium relative humidity of the grain.

Downward airflow aeration

**Advantages**
- In cool conditions, including those applying to sub-tropical conditions, the risk of moisture condensation under the storage roof and in the upper levels of grain is minimised.
- In the event that high relative humidity air is used for aeration, any moisture increase in the grain is spread over the entire surface area, rather than concentrated around the air inlet duct. [Not relevant where an elevated plenum floor is used.]
- Greater cooling can be achieved because there is no heating effect from the fan. This can be important in tall silos where high static pressures are required.

**Disadvantages**
- There is no air temperature increase and reduction in relative humidity caused by the fan. This can be important in sub-tropical climates for the reasons described above.
- The slowest area to cool is at the bottom of the grain bulk where monitoring of grain temperature is difficult.
- It is inappropriate where warm grain may be loaded on top of grain that has already been cooled by earlier aeration.
- Grain dust can be drawn down through the grain bulk and cause choking of the aeration ducts.
- In silos with suspended steel floors: under freezing conditions in temperate climates, air may be warmed and moistened as it is drawn down through the grain bulk. This can result in severe condensation when the air comes into contact with the silo base and cause ice build up in the grain, preventing emptying of the silo.

It can be seen from the above that there are no clear arguments in favour of one system or the other. However, in Australia, upward aeration is more common than downward aeration, and most users in the USA are firmly in favour of upward aeration for the reasons given above.

Air Distribution Ducting

The method of distribution of aeration or drying air into a storage is important from the point of view of obtaining an acceptable uniformity of airflow in the grain mass.
There are three main types of distribution systems:
- elevated perforated storage floor;
- above floor air ducts; and
- in-floor air ducts.

Elevated perforated storage floor

The most efficient and uniform air distribution into a grain mass is achieved with an elevated perforated floor in the base of the storage, which effectively provides a 100% contact area between the grain mass and the incoming air (Fig. 1). This type of floor is effective only in flat floored storages, and is more costly than the alternatives. It is, however, very commonly used in the central mid-west of the USA where in-store drying is prevalent; some silo suppliers in the region manufacture pre-formed floor panels which lock together with light gauge support legs to form a relatively low-cost elevated perforated storage floor, suitable for cleaning out with a sweep auger.

Above-floor air ducts

More commonly, air is ducted into the grain mass (or out of it, in the case of downward aeration) by means of air-ducts that are either built into the storage floor, or are placed on top of it. Above-floor ducts are less costly, but make emptying of the storage more difficult, particularly with end-loaders or sweep conveyors. Nevertheless, above-floor ducts are a practical engineering solution, particularly when retrofitting ducting to an existing storage floor, and they can be particularly useful in self-emptying bin bottoms where their protrusion above the floor surface does not inhibit the discharge of grain.

Above-floor ducts are usually made from corrugated perforated steel sheet which is rolled into circular or (more commonly) semi-circular shape and fitted to the floor of the storage. In flat storages where the grain height is low (less than 10 m), it is common to install the ducts in a manner that makes them easily removable to allow emptying of the storage with end-loaders and other portable equipment—for instance, round ducts may be secured with hoops or straps and fixed to the floor with bolts screwed into recessed sockets cast into the floor so as to avoid protrusions which interfere with cleaning when the ducts are removed (Fig. 2).

It is not possible to corrugate and roll plate thicker than 1.6 mm, hence in deeper bins, where grain pressures are high, it is usually necessary to reinforce the ducts with steel framing (Fig. 3). In the case of sloping (e.g. conical) bin bottoms, it is necessary to securely anchor the ducts to the bin floor to prevent them being dragged down the floor with the grain (Fig. 4). Structural analysis and design of these ducts is an art rather than a science, since the load imposed by the grain on a duct is somewhat indeterminable and, furthermore, the load capacity of a reinforced corrugated steel duct is not easy to estimate accurately. Interestingly, in the writer’s experience, few duct failures have occurred in bins of up to 2500 t capacity, whereas in larger capacity silos (5000 to 70 000 t) built in the 1980s, even heavily reinforced ducts have frequently failed as a result of unexpectedly high grain pressures.

An alternative to the use of corrugated rolled steel ducts, is the use of ducts formed with stainless steel ‘wedge-wire’, as used for the manufacture of rotary screens. Ducts formed from this material are extremely strong, and hygienic in that they largely prevent dust and broken pieces entering the duct through the apertures. They are, however, very much more expensive than corrugated perforated plate (Fig. 5).

Figure 1. Method of construction of elevated plenum floor of a type commonly used in the USA.
Figure 1. Reinforced half-round ducting often used in silo bases.

Figure 2. Typical circular aeration duct often used in horizontal storages.

Figure 3. Reinforced half-round ducting often used in silo bases.

Figure 4. Reinforced half-round ducting as used in conical silo bases.
Alternative above-floor ducts can also be formed from 'solid' plate without perforations, in such a way that allow air to escape around the bottom edges of the duct (Fig. 6). These are not commonly used in the writer's experience, but should work satisfactorily if they are made strong enough to resist the grain pressures imposed on them (Fig. 6).

**In-floor air ducts**

In-floor ducts are generally more expensive than above-floor ducts, because the duct has to be formed (usually in concrete), and covered by a perforated steel plate placed flush with the floor surface to allow unrestricted movement of equipment for cleaning the grain off the floor surface. The perforated plate must thus be flat, and therefore substantial reinforcement must be provided, for example, in the form of an open lattice grillage made from welded steel flats (Fig. 7).

Alternatively, it should be possible to use the folded perforated steel plate sections manufactured for elevated silo floors to form covers for in-floor ducts, although the writer has not seen this done.

Where portable equipment (such as end-loaders) are used to remove grain from the storage, the wheel loads imposed on the duct covers are often more severe than the grain loads, and thus govern the design of the cover supports.

**Duct Configuration**

**Horizontal storages**

In 'horizontal' (rectangular) storages, ducts may be aligned across the storage or along the length of the storage. Both have certain disadvantages as follows:

- **Cross-floor ducts.** In a storage where the grain is peaked in the centre by use of a longitudinal conveyor, cross-floor ducts pass under varying depths of grain. As a result, the airflow rate from the outer ends of each duct will be higher than from the middle unless the ducting is modified in some way to minimise this, for instance by enlarging the duct below the centre of the storage. This has the combined effect of reducing the velocity head, and thus increasing the static pressure. It also increases the cross-sectional and surface areas of the duct, thereby reducing losses in that region (Fig. 8).

- **Longitudinal ducts.** The floor of a large horizontal storage is often only partially covered—e.g. when the storage is partly filled. In such circumstances, longitudinal ducting is exposed in the unfilled areas, and large quantities of air will escape, bypassing the grain mass.

Cross-floor ducting is usually the preferred option for horizontal storages because it allows easier control of airflow into the grain.

Ducts should be spaced as follows:

- For in-store drying, the duct spacing should be not more than half the depth of the grain (Fig. 9). (Grain depth must be uniform for in-store drying.)
- For aeration, the duct spacing should be such that the longest air-path from a duct to the grain surface is no more than 50% more than the shortest path from the same duct to the grain surface (Fig. 10).

**Flat-bottom silos**

There are several options for air distribution systems in flat-bottom silos which are less expensive than an elevated floor. The options include on-floor ducts and in-floor ducts.

**Single radial duct.** A single radial duct with an external fan can be used for aeration in small silos. However,
duct enlarged at shed centre increases static pressure

cross-floor aeration duct

place fans at both sides of wide storages

Figure 8. Arrangement of cross-floor aeration ducts and lateral duct enlargement in a large shed.

Figure 9. Duct spacing for in-store drying.

Figure 10. Recommended spacing of longitudinal ducts.
for large silos the duct size becomes excessive, and the air distribution pattern is not adequate. Single radial ducts are unlikely to be acceptable for in-store drying in silos. Multiple radial ducts are seldom (if ever) used because each duct requires a separate fan.

Parallel ducts. Parallel floor ducts are commonly used for both aeration and drying, differing only in their size and spacing. Duct spacing requirements define the number and layout of the ducts. However, the designer has to select the manifolding arrangement for the fan or fans, unless each duct is to be fitted with a separate fan. A ‘tree’ formation of manifold and ducts is often adopted where multiple ducts are fed from a single fan since this minimises the effective length of the path for the ducted air (Fig. 11).

V-ducts. V-formation ducts are commonly used to distribute air from a single fan into the base of flat bottom silos (Fig. 12). For in-store drying, this arrangement is suitable for only relatively small diameter bins, since in larger bins the space between the ducts becomes excessive. V-formation ducts are almost always recessed into the floor of the silo.

Perimeter ducts. Perimeter ducts have been successfully used for grain aeration in some relatively large (3000 t) flat-bottom silos designed by the author (Fig. 13). The aim was to provide good air distribution while leaving the silo floor free of protuberances. Quarter-round corrugated perforated steel plate was used to form the ducts, and each section of duct was hinged against the silo wall to permit easy access for cleaning broken and dust.

Circumferential ducts. In ‘squat’ silos (i.e. silos with small wall-height to diameter ratio), the grain depth varies significantly from the outer perimeter to the centre of the silo. The length of airflow path (and hence the static pressure needed to force the air through the grain mass) thus varies significantly from the silo wall to its centre. Parallel ducts placed in the floor (even an elevated bin floor), are likely to result in a concentration of airflow towards the outer perimeter of the grain mass (where the airflow resistance is least) and substantially less airflow in the centre of the silo. The author has recently designed a system of circumferential in-floor ducts for grain aeration in such silos, each fitted with its own fan (or fans), and each duct and fan ‘set’ individually sized to suit the mass of grain above it. Thus, the fan serving the centre of the bin has a relatively low airflow rate but high static pressure, while the fan (or fans) serving the perimeter of the bin have a high airflow rate (because of the larger volume of grain around the perimeter) and a low static pressure (because of the lower grain depth). The system is so far untried, but is expected to be put into use on a project in China in the near future (Fig. 14).

Figure 11. Typical parallel duct arrangement in a flat floor silo base.
Figure 12. Typical V-duct arrangement in a flat-bottom silo.

Figure 13. Arrangement of perimeter ducting in relatively large flat-bottom silos.
Hopper bottom (self-emptying) silos

Hopper bottom silos are not often used for in-store drying of grain, since they are usually associated with high throughput requirements, which are generally inconsistent with the requirements for in-store drying. Aeration equipment is, however, often fitted to hopper-bottom silos to allow the silos to be used for ‘holding’ the grain for short periods without deterioration before shipping. Aeration is also often fitted to hopper bottom bins for cooling of grain after drying.

Aeration ducting in hopper-bottom silos is usually either perimeter-type or radial-type or a combination of both. Above-floor ducts are used in hopper bottom silos since there is no special advantage (but large extra costs) in building them in-floor.

Vertical ducts

Vertical ducts attached to the silo walls have occasionally been used for aeration of bins in such manner that air is blown (or sucked) horizontally across the grain in the silo, out from one duct and into the other. Apart from requiring long ducts (full wall height) which are difficult to install, the biggest problem with them is the same as with longitudinal ducts in horizontal storages—they must be covered with grain if they are to work, and it is not possible to aerate a partially filled silo with them. There are few, if any, circumstances where they can be recommended.
Airflow Resistance in Ducts

Air movement in ducts

Air passing through ducts will lose energy from frictional effects associated with the duct shape, surface, turbulence, etc. This loss of energy results in a gradual loss in 'total pressure' (or head) as the air moves through the duct.

Total pressure is the sum of the static pressure and the velocity pressure. Static pressure is the 'normal' pressure that the air applies to the walls of the duct that it passes through; velocity pressure is the component of pressure that results solely from the movement of the air, and is equal to \( V^2/2g \), where \( V \) is the velocity of the air, and \( g \) is the acceleration due to gravity. As air passes through a duct system, its velocity will change where the duct size changes; thus, where the duct size increases, the velocity pressure will decrease and the static pressure will increase, and vice versa. Along the duct system, however, the total pressure (the sum of the velocity and static pressures) will gradually diminish.

Airflow resistance in ducts depends on the size, shape, and smoothness of the duct and the velocity of air passing through it and the temperature of the air. Friction losses in straight ducts are normally determined from charts, elbows, bends, T-junctions, etc. can add significantly to friction losses—for instance, a single right-angle 'mitre' bend in a square duct is equivalent to adding a straight duct with a length of about 75 times the depth of the duct. (Note: giving the bend a radius equivalent to the depth of the duct reduces the friction loss to an equivalent length of duct 1\( \sqrt{11} \) times the depth.)

In most grain aeration and drying situations, duct lengths are short and few bends are required. In most circumstances, provided the air-velocity is kept low enough (see below), friction losses in ducts are small compared with the losses in the grain.

Air movement through duct perforations

The pressure drop through a perforated duct covered with grain can be estimated from Equation (3) (Brooker et al 1992):

\[
\Delta P = 1.07 \left( \frac{Qa}{eO_f} \right)^2
\]  
(3)

where: \( e = \) void space in grain (%) and \( O_f = \) percentage opening in duct surface (%).

where: \( O_f > 10\% \), the pressure drop through the duct can be ignored.

Selection of air-duct sizes

Much work has been done recently in refining the methods of determining the optimum size of ducts for distributing air into a grain mass, and software is now available for carrying out these calculations (Wilson, S.G. 1991. Duct: a PC Program for designing seed store ducts. Personal communication). However, in the absence of such tools, there are two well-recognised 'rules of thumb' which can be used to estimate the size of ducting that will minimise head losses.

- The cross-sectional area of the duct should be large enough such that the velocity of the air in the duct is not more than 10 m/second.
- The surface area of the duct should be large enough such that the escape velocity of the air from the duct into the grain is not more than 0.15 m/second (assuming a duct perforated area of approximately 10%).

Commonly used perforations suitable for grain aeration are 2.5 mm diameter holes at 6.25 mm (triangular) centres, giving an open area of around 15%.

Airflow Resistance in Grain

There are various methods of determining the resistance of airflow through a grain mass, from which the fan characteristics and power requirements can be determined. Holman (1966) presented a simple graphical method in the form of curves for different types of grain, relating bed depth to static pressure, from which fan power could be determined.

Shedd’s formula (Equation 4) is another method which can be used to calculate the airflow resistance per unit metre of grain depth:

\[
\Delta P' = \frac{aQ_a^2}{\ell n(1 + bQ_a)}
\]  
(4)

where \( \Delta P' = \) pressure drop per unit depth of grain \( Q_{\ell i} = \) airflow rate per unit area of floor

\( a \) and \( b \) are Shedd’s constants which vary for each type of grain. Constants for some common grains are given in Table 5.

Shedd’s formula gives results that are satisfactory for clean grain in small storage, but it does not reliably account for dirty grain or for deep masses of grain. It is suggested that the calculated pressure drops be increased by at least 50% to allow for factors that could restrict the airflow. Various studies have been conducted under a range of grain conditions from which Shedd curve multipliers can be determined based on variations in fines content, moisture content, filling method, and airflow direction (Brooker et al. 1992). It appears from some of these results that:
• a 3–5% fines content can increase airflow resistance by 50% above that for clean maize;
• the pressure drop per metre of maize reduces by about 50 Pa/metre per m³/sec/m² of air flow ($Q_a$), for each 1% increase in moisture content; (the pressure drop for wheat changes by 200 Pa/metre per $Q_a$ per 1% increase in moisture content);
• the use of mechanical grain spreaders in the inlets of silos can reduce airflow resistance significantly below Shedd’s values; and
• the resistance to airflow through grain in a horizontal direction is significantly lower than in the vertical direction.

**Table 5.** Shedd’s constants for airflow resistance.

<table>
<thead>
<tr>
<th>Grain</th>
<th>$a$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>$2.70 \times 10^4$</td>
<td>8.77</td>
</tr>
<tr>
<td>Shelled maize</td>
<td>$2.07 \times 10^4$</td>
<td>30.40</td>
</tr>
<tr>
<td>Paddy</td>
<td>$2.57 \times 10^4$</td>
<td>13.20</td>
</tr>
<tr>
<td>Sorghum</td>
<td>$2.12 \times 10^4$</td>
<td>8.06</td>
</tr>
<tr>
<td>Barley</td>
<td>$2.14 \times 10^4$</td>
<td>13.20</td>
</tr>
<tr>
<td>Oats</td>
<td>$2.41 \times 10^4$</td>
<td>13.90</td>
</tr>
<tr>
<td>Rapeseed</td>
<td>$3.99 \times 10^4$</td>
<td>4.20</td>
</tr>
<tr>
<td>Soybeans</td>
<td>$1.02 \times 10^4$</td>
<td>16.00</td>
</tr>
<tr>
<td>Sunflower (oilseed)</td>
<td>$2.49 \times 10^4$</td>
<td>23.70</td>
</tr>
</tbody>
</table>

Source: (ASAE Standards 1988)

**Selection of Fans**

Having determined the required airflow rate and the pressure drop in the system, it is a relatively easy matter to select the appropriate fan to meet the performance criteria.

Selection is best made from performance curves supplied by manufacturers. However, there are a few basic guidelines that designers should be aware of:
- Axial fans are most suited where static pressures are predicted to be less than 1 kPa. Above 1 kPa, centrifugal fans are likely to be more efficient. Thus, axial fans are usually used for aerating shallow depths of grain, whereas centrifugal fans are more commonly used on vertical silos.
- Axial fans are not generally suited to grain drying.
- Axial fans are noisier than centrifugal fans because they usually operate at around 3000 rpm (compared with 1500 rpm for centrifugal fans). Sound attenuators may need to be fitted in noise-sensitive localities.
- Centrifugal fans should normally be of the backward-curved-blade non-overloading type. Use of this type of fan avoids overloading of the motor in situations when the airflow resistance is lower than normal and airflow rate higher than predicted—for example, when the storage is only partially filled. Fans with forward curved and straight blades will draw more air (and current) under such conditions, causing motor overloading.

Where a storage is designed so that it can be sealed for fumigation, the designer should specify fans that are readily sealable, and which have no exposed copper components which can be chemically attacked by phosphine gas. In the case of centrifugal fans, this may require minor modifications to the fan casing, for instance to allow bolting of a ‘blanking’ plate over the air inlet, and a gland or stuffing-box seal should be fitted where the impeller shaft enters the fan casing. Axial fans may need to be removed during fumigation with phosphine unless the motor and wiring can be sealed sufficiently to prevent entry of phosphine.

**Conclusion**

The paper describes the basic principles for the design of aeration and in-store drying systems. Space precludes a complete coverage of the subject, and designers should refer to some of the standard texts in the reference list for more detailed information, particularly relating to particular circumstances. The design parameters offered in this paper have been used by the author in a number of installations, and they have given good service in practice, which indicates that the parameters are at worst conservative and at best reasonably sound.

**References**


USDA (United States Department of Agriculture) 1965. Drying shelled corn and small grain. USDA Farmers Bulletin 2214.
Further Reading


Control Systems for Aeration and Drying of Grain

G. Srzednicki*

Abstract
Automatic control systems are becoming increasingly popular in grain drying processes. They include measurement, steering, monitoring and recording functions. The advantages include improvement in the product quality, minimisation of energy use, optimisation of labour inputs, and increased effectiveness. A good understanding and analysis of the drying process is essential for the design of a control system. The control systems for in-bin aeration and drying systems aim to regulate the fan operations. They will also control heater operations whenever heat is added to the drying air. In continuous-flow dryers, the parameters controlled are the drying air temperature and the speed of augers. The most common control systems used for grain drying are discussed. With increased interest in mechanical drying of grain under tropical conditions, the possibilities for introduction of automatic controllers are currently being investigated. This is occurring as a spin-off of the adaptive research in in-store drying that has been conducted over the last ten years by several ACIAR projects in Southeast Asia. It can be expected that the increasing adoption of mechanical drying systems in the countries of the region will be followed by the introduction of control systems to optimise the use of the equipment.

Automatic control plays an increasingly important role in the modern production processes and logistics. Even a well-trained operator cannot optimise a process purposefully and unequivocally. This is because production processes often involve non-linear relationships and dependencies. Rapid progress in the theory and practical applications of control systems has contributed to an improvement of productivity and performance optimisation. Also, reduction of fatigue of operators performing monotonous and repetitive tasks has resulted in a decrease in human errors. Operations involving temperature, humidity, pressure, speed, and viscosity will normally be controlled by microprocessor-based systems. Mathematical models are the basis for computer simulations that enable engineers to define the statistical limits of values for parameters that are usually subject to random effects. The great advantage of this approach is the move from an empirical to a model approach, where changes in values of parameters can be tested quickly instead of time-consuming building and testing of prototypes.

The control systems originated in the eighteenth century in the form of a speed controller for a steam engine designed by James Watt. Modern control theory emerged between World Wars I and II, through the work of Minorsky on ship steering controls that could be derived from differential equations describing the system. Later, Nyquist developed procedures to determine the stability of closed-loop systems based on the response of open-loop systems to the response of steady-state sinusoidal inputs (Ogata 1990). A very rapid development of control systems took place on the arrival on the market of affordable digital computers. This led to the widespread use of control systems in diverse areas including manufacturing, biological and biomedical applications, and transport and entertainment.

A sound understanding of the process that is to be controlled is essential for the design of a control system. The initial analysis examines the requirements of production and the capacity of the equipment used, the proposed control strategies, and the schedule of operations. It also includes an initial analysis of the potential benefits of the system.

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Mechanical drying, as an industrial operation, has seen applications of control systems for many years, especially for large-scale operations. However, with the decrease in cost of microprocessors, control systems have become increasingly accepted to capture the same advantages that they have brought to other areas of industrial production.

Grain Dryer Controls

Drying of grain to reduce the water activity of the product is the safest method of preserving grain from further deterioration during storage. The main types of dryers are in-bin dryers, using ambient air with or without supplemental heat, and continuous-flow dryers using heated air. There are also combinations of both systems, developed within the concept of two-stage drying. In a two-stage drying system grain is dried using a high-temperature fast dryer down to a moisture content of about 18% wet basis (w.b.), and then down to a safe storage moisture content (generally 14% w.b.) in an in-bin dryer using near ambient air. The latter is called an in-store dryer since grain will be stored after drying in the same bin or store (Srzednicki and Driscoll 1994). During extended storage, grain will usually also be aerated in order to further reduce the risk of deterioration.

The two main types of grain dryers require specific control systems related to their mode of operation. However, the principal objectives of the control systems are the same:

- uniform moisture distribution in the mass of grain without over- or under-drying;
- prevention of grain deterioration;
- optimum grain quality;
- maximum capacity; and
- low energy consumption.

Controllers, relevant components of the dryer, and the operator interact to achieve these objectives. The level of the interaction is used to classify different types of controls as follows (Pym and Adamczak 1986).

Manual systems

Information about the process is collected by the operator on dials or chart recorders and analysed according to established procedures or experience. The decision is made by the operator and translated into action through manually operated switches or levers.

Supervised systems

These could also be called semi-automatic systems. The operator receives information about the ongoing process on displays with adjustable setpoints that are providing a partial feedback control. However, some decisions have to be made by the operator according to established procedures and translated into action by adjusting setpoints or switches.

Automatic systems

Here, the function of the operator is largely taken over by a microprocessor that is programmed to interact between the information supplied by the sensors and the appropriate action to be taken by relays or actuators. The system will automatically handle most of the alarm conditions and also provide automatic reporting. There is still need for an operator to reset the system in case of a power failure or emergencies, but their involvement will be minimal as compared with the two previous systems.

Automatic control systems use algorithms based on mathematical models representing physical and chemical characteristics of the process, and information obtained through simulation or experiments. Mathematical simulations describe the process with sufficient accuracy to predict the result without the need for use of empirical methods. The introduction of automatic controls results in optimisation of performance of dynamic systems, in increased productivity, and in a reduction in drudgery and the risk of human error.

Control theory uses specific terminology that is defined in a number of textbooks (e.g. Shinskey 1988; Ogata 1990). The following terms are used throughout this paper:

- A controlled variable is a quantity or condition that is measured and controlled.
- A manipulated variable is the quantity or condition that will be changed in order to achieve the desired value of the controlled variable.
- A closed-loop system or feedback control is a system that reduces error in order to produce required output. The latter is generally referring to the product created by the process.
- An open-loop system is one in which there is no relation between control action and output.

Control Systems for Continuous-flow Dryers

Continuous-flow high-temperature dryers are used for drying large quantities of grain, generally in several passes, from field moisture down to at least 18% w.b. moisture content. This is a continuous operation involving grain of different initial moisture contents and therefore requiring appropriate adjustments of the residence time. The main types of continuous-flow dryers used in the grain industry are:

- crossflow;
- concurrent-flow;
- counterflow; and
- mixed-flow.
A comprehensive review of control systems for continuous-flow dryers can be found in papers by Bakker-Arkema et al. (1990) and Moreira and Bakker-Arkema (1992). The following cover the key points.

The residence time of grain in the dryer is the factor that determines the final moisture content and consequently the quality of the grain. Over-drying and under-drying are undesirable and lead to reduced profits of the plant. The operator or the control system has to adjust the speed of the unloading auger for a given temperature and initial moisture content of the grain. Control systems have been developed in order to minimise over-drying and under-drying of grain as compared with the manual intervention of the operator. An evolutionary process led to development of five generations of controls.

**Classical feedback control**

In earlier days, the operator checked the inlet and outlet moisture content on an hourly basis and adjust the speed of the auger manually. The first automatic controllers were temperature-triggered feedback controllers, measuring the temperature of the grain or of the exhaust air at different locations in the drying column. However, because of the non-linearity of the drying process, and lack of a consistent relationship between the moisture content and the temperature of the exhaust air, such systems were unreliable, especially if the moisture content changes exceeded 3% w.b. For this reason, the temperature-activated systems have gradually been replaced by moisture-activated ones.

The classical feedback controls are based on proportional-integral (PI) or proportional-integral-derivative (PID) closed-loop controls using algorithms that minimise the error between the output and the controlled variable. These controllers perform well if the relationship between the controlled and the manipulated variable is linear and if the time response is short (Whaley 1995). As already mentioned, nowadays, the controlled variable in this case is the grain moisture content. However, the classical feedback system is unstable if the moisture range is wide. This is due again to non-linearity of the drying process and the grain flow. An attempt has been made by Whitfield (1988a,b) to overcome this problem by modifying the control algorithm so as to increase the bandwidth of moisture range. This implies an initial tuning of parameters by the operator as well as recalibration, especially if there are differences in the bulk density of the grain. Another problem, common to all feedback controllers, is a slow response of the controls in case of long residence time in the dryer. In recent times, attempts have been made to increase the robustness of the controls by using linearising transformations in the control software (Courtois et al. 1995)

**Optimal feedback control**

This type of control uses an algorithm based on a process model approximating the drying model. The technique used attempts to minimise the governing equation by quadratic programming. In spite of the great accuracy of this type of control, the difficulty in defining the governing equation and a high computational requirement make this type of control unlikely to be adopted on a commercial scale.

**Feedforward control**

The principle of this type of control is based on a continuous or intermittent measurement of the main load variable, i.e. the initial grain moisture in a continuous-flow dryer. The residence time is calculated by the model based algorithm and the response time is very short. Differential equations have been developed for the transient analysis of concurrent-flow, crossflow, and mixed-flow dryers. Empirical models have then been derived from the differential equations in order to simulate the operation of each of these three types of dryer. Whitfield (1986) used a steady-state simulation to predict unsteady states caused by varying inlet moisture contents for controlling concurrent and counter-flow grain dryers. Moreira and Bakker-Arkema (1990a) developed a partial differential equation model that describes the unsteady-state operation of a two-stage concurrent-flow dryer for maize. This model was used to design an automatic control system for such a dryer. Platt et al. (1991, 1992) combined a feedforward and feedback control in order to incorporate the use of optional features for cross-flow dryers, such as inverters (aiming at reducing gradients in grain temperature and moisture across the dryer) and air recirculation. Bruce and McFarlane (1993) developed a feedback-plus-feedforward algorithm that eliminates the influence of variations in drying air temperature in mixed-flow dryers.

**Adaptive control**

The previously described feedback and feedforward controllers are characterised by fixed parameters used in the control law. Since a dryer operating under normal commercial conditions faces the problem of fluctuations in inlet grain moisture and temperature of the drying air, this type of control system often results in inaccurate control, leading to increased variability of the final moisture content in grain. The adaptive control system enables the controller to tune itself in spite of such fluctuations. A number of researchers worked on the process model for adaptive control. A moisture-activated feedforward controller for a crossflow dryer has been developed by Forbes et al. (1984). Nybrant (1988) developed an adaptive feedback controller for crossflow dryers, based on a linear model.
using exhaust air temperature, Eltigani and Bakker-Arkema (1987) developed an adaptive model based on feedforward control for crossflow dryers. It is a two-term linear model with model parameters estimated by the sequential least square method. An adaptive feedforward/feedback control for crossflow dryers has been developed by Moreira and Bakker-Arkema (1990b). Two linear models have been proposed by the authors, namely the generalised minimum variance controller and the pole placement controller. The pole placement controller was found to be faster, required fewer parameters to be estimated, and was easier to implement. It controlled the final moisture content of grain within ±0.1°C of the set-point for a moisture content differential of ±2.3% w.b. in the incoming grain.

Fuzzy logic (expert) controllers

The complexity of the control objectives, especially when the quality aspects of grain are concerned, often make them difficult to achieve using conventional controls based on a set of governing equations. This is often due to insufficient understanding of such phenomena as breakage susceptibility. Therefore, research has been carried out in recent years on fuzzy logic control and neural network strategies control that combine mathematical models of the drying process and the experience of the operator. The result is a set of rules, kept in a knowledge base, that convert linguistic control strategies into automatic commands (Zhang and Litchfield 1993, 1994). The rules are represented as membership functions called fuzzy membership matrices. The difficulty in implementing this type of control is that there is a large number of rules associated with fuzzy membership matrices. In order to implement the fuzzy logic control, the membership functions have to be fine-tuned using a wide range of process conditions, which often proves very time consuming. Although very promising at an experimental stage, fuzzy control usually requires a considerable amount of historical process data in order to be included in industrial applications.

Control performance assessment

Douglas et al. (1992) describe a method for quantification of control performance of moisture controllers for continuous-flow dryers. The authors introduce two indicators of performance called performance measures PM1 and PM2. They are defined as follows:

\[ PM1 = \frac{S_{NT}^{\text{out}}}{S_{\text{out}}} \]  
\[ PM2 = \frac{\text{OS}_{\text{allowable}}}{\text{OS}_{\text{actual}}} \]  

where \( S_{NT}^{\text{out}} \) = outlet standard deviation of the moisture under 'no touch' control, and \( S_{\text{out}} \) = outlet standard deviation of the moisture with control.

The performance measures reflect the product moisture variation and the deviation of the mean from the target. The higher the value of the two indicators, the better is the performance of the dryer. Both performance measures can be used to compare performance of various types of continuous-flow dryers.

Control Systems for In-bin Dryers

The term 'in-bin dryers' describes a drying system that uses a fan and an air distribution system that will force drying air through the bulk of grain. The grain is contained in a bin that can be a metal or concrete silo or a horizontal warehouse. There is a range of types and sizes, varying in capacity from about 30 to several thousand tonnes. There are also various types of air distribution systems, such as perforated floors, in floor or on-floor horizontal perforated ductings, and vertical perforated ductings.

In-bin dryers can be one or other of two types. In the high temperature type, hot air is blown through a shallow depth of grain in order to achieve rapid drying. In the other type, air of near ambient temperature, or only slightly heated (usually by a maximum of 5°C above ambient) is passed through the grain mass. The relative humidity of the drying air corresponds to the equilibrium moisture content of grain that can be stored safely without significant deterioration. Grain can be dried in deep layers in the same bin, silo, or warehouse in which it will be stored. This technique is also called in-store drying.

During extended storage, grain that has already been dried, will need to be aerated in order to:
- reduce the grain temperature and prevent it from deterioration;
- equalise the temperature throughout the bulk of grain;
- control insects by preventing formation of hot spots; and
- prevent formation of off-odours.

The control system for in-bin drying or aeration is of the open loop type, which means the output is generally not measured or fed back to be compared with the input. The control acts on the fan and heater in high-temperature dryers and in-store dryers equipped with heaters, or on the fan alone in in-store dryers using only ambient air and in grain aeration systems. The measured variable is the temperature or relative humidity of ambient air, whereas the controlled variable is the temperature or the relative humidity of the drying air. The grain temperature is an indication of
the progress of drying. In grain aeration, grain temperature may become the measured variable, triggering the fan action.

There are various performance criteria associated with the use of control systems in in-bin drying (Bakker-Arkema et al. 1990; Ryniecki et al. 1993b). Among the most commonly used are:

- energy consumption;
- over-drying;
- spoilage estimated by different methods (e.g. spoilage index, dry matter loss, etc.); and
- drying time.

Over twenty strategies have been proposed to meet these criteria (Moreira and Bakker-Arkema 1992). They involve a range of parameters such as time, temperature, or relative humidity of the drying air, target moisture content in the top layer of the grain bulk, or estimated dry matter losses. Grain drying mathematical models estimating the average moisture content of the grain bulk or grain quality criteria have been used to write control algorithms. Ancillary equipment aimed at improving the uniformity of drying (grain stirrers) and reduce the energy consumption (recirculation) has been included in the control systems with varying degrees of success (Srzednicki and Driscoll 1994). Studies aimed at optimising values of control parameters are usually based on repeated computer simulations involving a large amount of historical weather data. Stochastic models of heat transfer in a thin-layer of grain and of ambient air temperature variation have been developed in order to further optimise the value of control parameters (Ryniecki and Jayas 1992). Most of the control strategies are based on experience, but some involve mathematical optimisation techniques (e.g. Ryniecki 1991; Ryniecki and Nellist 1991a,b; Ryniecki et al. 1993a,b). Ryniecki et al. (1993a, b) compared two locations with different climatic conditions, one maritime (England), the other dry continental (Canada). A large number of computer simulations using 20 years of weather data on a hourly basis has been run using different control strategies, based on relative humidity of the drying air with fixed or variable power heater or without heater, for near-ambient air temperature drying of wheat. The above-mentioned performance criteria have been used to assess the effectiveness of the process. The authors found that a fan and heater combination with variable power heater was the optimum system for the humid maritime conditions of England, whereas a fan-only system proved to be the optimum for the dry continental conditions of Canada. Furthermore, it was found that, for the fan-only system, variable airflow significantly reduced over-drying, energy consumption, and subsequently the drying cost as compared with fixed airflow. However, a variable speed drive needed to vary the airflow rate implies additional investment in the drying plant. As a result of this work, it appears that the choice of the strategy depends very much on the climatic conditions of the site and requires a careful study of the weather conditions before the selection of a control strategy.

In high-temperature in-bin dryers the control is focusing on the temperature of the drying air and is the simplest of control systems for in-bin drying. As for the near-ambient temperature drying, the following strategies have been commercially adopted:

- continuous aeration with additional heat (max. ΔT = 6°C);
- relative humidity control with upper limit;
- relative humidity control with lower and upper limit; and
- self-adjusting equilibrium moisture content.

Grain aeration being a technique to maintain the quality of grain in storage consists in blowing cool air through the grain bulk. In temperate countries this process can involve cold ambient air during winter months, cool air during the night, or artificially cooled air if ambient air temperature is high. The control strategies consist in aerating either at regular intervals, using a timer, an air temperature based time proportioning controller (Pym and Adamczak 1986), or a grain temperature based system, activated by increasing temperatures in the grain. The difficulty with the time proportioning controller is that it disregards the relative humidity of ambient air and introduces the risk of grain rewetting.

Applications of Control Systems under Humid Tropical Conditions

Southeast Asia is one of major grain-producing areas in the humid tropics. Rice and maize are by far the main cereal crops grown in the area. Two or more crops per year are becoming a permanent feature in most of the countries. This implies that some of the annual crop will be harvested during the wet season. The region is currently characterised by very rapid economic growth resulting in higher purchasing power and increased demand for quality grain. In order to meet the demand and the export requirements, the grain industry is improving the productivity, resulting in increasing adoption of modern technology in grain drying. Large grain complexes and mills are nowadays using high-temperature dryers, and control systems are often supplied as an option by the manufacturers.

The two-stage drying technique with in-store drying as a second stage is also being adopted by the grain industry (Srzednicki and Driscoll 1995). The technical feasibility of in-store drying under humid tropical conditions has been established through col-
laborative work over the past 12 years between the Australian team from the University of New South Wales and research teams in the Philippines, Malaysia, Thailand and, more recently, Vietnam (Driscoll 1987; Rukunudin et al. 1988; Driscoll and Adamezak 1988; Srzednicki and Driscoll 1992). Already, during the early stages of the research, some attention was given to control systems for in-store dryers (Driscoll et al. 1989). As previously mentioned in comparing the strategies used for humid maritime and dry continental climate, in-store drying in the humid tropics requires a fan and heater for the wet season. Meanwhile, during the dry season, drying of grain can be performed satisfactorily using a fan only. The following four strategies have been devised and tested:

a) time clock control (including continuous aeration);
b) drying air temperature control;
c) relative humidity control; and

d) modulated burner control.

Given the fact that mechanical drying is still a new technique, slowly gaining ground against sun drying, especially during the dry season, it is difficult to justify additional investment in automatic control systems. An experienced operator will often be capable of switching on the fan at certain times or off when relative humidity is outside a suitable range for drying. A thermostat will also provide a crude control of the drying air. However, optimisation studies comparing drying cost for three of the above four strategies (a, c, and d) in different locations throughout the region (Malaysia, Philippines and Thailand) in dry, wet, and average years, for paddy and for maize, have shown that relative humidity control was the least expensive strategy followed by continuous aeration (Srzednicki and Driscoll 1993). The trend to generate supplemental heat by use of a rice hull furnace is reducing considerably the cost of heat energy in Vietnam (Phan Hieu Hien and Nguyen Le Hung 1995). Rice hull furnaces for in-store dryers are also under development in Thailand and the Philippines.

As far as aeration is concerned, a grain cooling system aiming at maintaining grain temperature at 19–20°C has been implemented at seventeen grain complexes of BERNAS, the recently corporatised rice handling authority in Malaysia (Teoh and Hassan 1995). The control system is based on the grain temperature and cooling is triggered by the maximum temperature grain is allowed to reach.

**Hardware for Control Systems**

The most commonly used process control methods today incorporate digital controllers. Among them is a considerable number of PID type feedback single loop controllers. Larger control systems will use programmable logic controllers (PLC). PLCs handle well a linear process with large time constants. However, model based controls will often require a large computational power and will require the use of process computers. The prices of PLCs and microcomputers have fallen considerably in recent years, making them more affordable for potential users. Sensors are an essential component of the system. There is a wide range of qualities and prices. Some of the sophisticated in-line moisture meters for continuous-flow dryers may be worth an equivalent of a medium capacity dryer. It is obvious that their chance of adoption is limited to very large capacity units, generally owned by large grain authorities.

As far the control system for in-store drying is concerned, given that it is based on the temperature or relative humidity sensors, plug-in data acquisition cards offer a cost-effective alternative to PLCs. Plug-in data acquisition boards plug directly into the expansion bus of a PC. Multi-function data acquisition boards include analog/digital converters, digital input/output ports as well as counter/timer circuitry. A multi-function card (Fig. 1) can be interfaced with a signal conditioning board for analog data input (from sensors) and a relay board that triggers different actions required by the process (e.g. fan, heater, dampers).

**Conclusions**

Control systems for grain dryers have shown rapid development in the last fifteen years. For high-temperature dryers, the control parameters are exit air temperature or the moisture content of the inlet and of the exit grain on one hand, and the speed of the discharge auger on the other. The grain moisture based controls are more accurate, but the cost of the system is higher, primarily due to the cost of the sensor. Among the commercially adopted systems are the classical feedback control and the adaptive feedback/ feedforward control. The feedback control is generally slow if the residence time is long. The adaptive feedback/feedforward controller provides fast response and reduces the fluctuations of the moisture content in the exit grain irrespective of fluctuations in the moisture of the inlet grain.

As for the control system of in-bin drying, the controller acts on the fan and the heater, if the latter is required. The climatic conditions of the location determine which strategy is to be adopted. A single strategy may only partially satisfy the performance criteria (low energy consumption, prevention of over-drying, low spoilage, short drying time). Optimisation techniques are being used in order to reconcile the performance criteria.
Control systems are also being introduced for in-store drying in the humid tropical climate of Southeast Asia. Relative humidity control and continuous aeration prove to be the most successful techniques for a range of climatic conditions in Southeast Asia. However, the rate of adoption of controllers is slow, except for large capacity dryers. This situation is related to relatively high cost of control equipment as compared with low margins for high quality grain. Plug-in card based systems may become an attractive option, promoting adoption of automatic controllers and resulting in improvement of grain quality and reduction of the cost of grain processing.

References


