Grain Dryer Controls: A Review

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ABSTRACT

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The technology of in-bin and continuous-flow grain dryer controllers was assessed. In-bin controls are usually of the heuristic type. Control for continuous-flow grain dryers is of either the classical feedback or the adaptive feedforward type. Moisture-based control is recommended for large variations in moisture content. Several commercial controllers were evaluated. It was concluded that controllers have finite grain-quality and cost advantages when installed on in-bin and continuous-flow systems.

Cereal grain is often harvested at moisture contents that are too high to permit storage of the grain without spoilage for the selected storage period. Different treatments are available to preserve grains at high moisture contents; drying of grains is the most widely used grain-preservation method.

Grain dryers fall into two categories: batch dryers and continuous-flow dryers. In batch dryers, the grain is dried either with heated air in shallow layers of less than 1 m or with low-temperature air in beds of several meters in depth. The drying may take place in hours, days, weeks, or even months. Continuous-flow dryers are high-capacity dryers and are classified according to the relative direction of grain and airflow such as: crossflow, concurrent-flow, counterflow, and mixed flow.

The objective of this article is to critically review the most important recent studies of grain dryer controls. The grain dryer control systems considered fall into two categories: in-bin aeration and drying controllers and continuous-flow dryer controllers. The basic objectives are usually the same for both controller types, namely, to achieve a uniform final moisture content while maximizing the capacity under acceptable conditions of grain-quality deterioration and energy consumption.

The control of in-bin drying or aeration systems consists of controlling the fan operation and sometimes the heaters. In continuous-flow dryers, the speed of the unload augers and the temperature of the drying air are the control parameters.

Overdrying of grain is costly, mainly because the price of grain is based on a specific moisture content. At the present time (July 1991), with the U.S. price of corn at $2.26/bu, overdrying one million bushels (25,402 t) by 1.0% (i.e., to 14.5%) results in shrinkage losses of $26,431 and in additional energy costs (at $5.00/$10^6$ BTU) of $10,570. Added to this $37,001 should be an unspecified quality-premium loss due to the increased number of stress-cracked kernels in overdried corn (OTA 1989).

Manual control of a drying system (in-bin or continuous-flow) is a complicated task. It requires extensive experience on the part of the dryer operator not to overdry or underdry the grain while operating a dryer under acceptable conditions with respect to grain-quality deterioration and fuel consumption. A well-designed controller substitutes for expertise and in fact outperforms an experienced operator.

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IN-BIN CONTROLS

In-bin controllers are employed to control 1) grain aeration and 2) natural-air or supplemental-heat grain drying. The hardware of the two controller types is similar, but their software differs. The controller strategy used for in-bin grain drying is of the open-loop type. Two different approaches are usually considered: heuristic (based on experience) and optimization (based on mathematical programming).

In-bin control systems usually measure the temperature and relative humidity of the ambient air and the temperature of the grain. Some sophisticated controllers also measure the relative humidity of the air in the interstices of the grain mass (Pym and Adamczak 1986). The proper location of the temperature and relative humidity sensors is critical, especially of those placed in the bin. Control actions are based partially on the maximum temperature and equilibrium relative humidity of the grain, and thus the sensors should be located where these maximum values are likely to occur. It is recommended that the cable with multiple temperature sensors be placed in the center of the bin under the loading spout and at 0.6–0.9 m from the wall in the southwest sector of the bin. The use of a series of cables increases the chance of detecting a hot spot; the selection of the number of cables is obviously an economic compromise (Kelley et al 1990).

Modern in-bin controllers are equipped with microprocessors that allow the user to change the strategy of the control action. Usually, in-bin control systems do not require extensive control calculations. Since the hardware and software are simple, the cost of an in-bin control system is moderate ($3,000–5,000 in U.S. dollars [as of December 1990]).

Control Strategy

In-bin controllers usually have two operation modes, one for drying and one for aeration and storage. Controller manufacturers (AgriDry, Inc., Orrville, OH; Pertech, Inc., Chaska, MN; and Sentry Technologies, Inc., Chanhassen, MN) use proprietary control strategies for each operation mode. A series of simulation studies has been conducted on in-bin drying or aeration control strategies (Pfost et al 1977, Morey et al 1979, Colliver et al 1983, Mittal and Otten 1983, Gunasekaran and Shove 1986, Brook 1987, Lynch and Morey 1989, Ryniecki and Nellist 1991). Only a few experimental investigations have been published on in-bin controllers (Morey et al 1979, Lynch and Morey 1989, Kelley et al 1990). The most significant results of the simulation studies and the experimental investigations of in-bin control systems are analyzed and evaluated.

To evaluate a particular control strategy, agreement is necessary on the performance measure or objective criterion of a drying or aeration treatment. Ten potential performance criteria are given in Table I. Since a particular control strategy can minimize (or maximize) only one performance measure, it is theoretically possible to manage the drying or aeration of a bin of grain in 10 different ways and still claim that each operation is optimal. Thus, it is essential that a prospective buyer of an in-bin controller understand the objective for which the controller has been designed.

TABLE I
Potential Performance Criteria for the In-Bin Drying or Aeration of Grain with a Programmable Controller[a]

Criterion Number	Criterion
1	Minimize fan operation (hr)
2	Minimize overdrying (%, wb)
3	Minimize moisture content range (%, wb)
4	Minimize time to finish drying (hr)
5	Minimize average dry matter loss (%)
6	Minimize maximum dry matter loss (%)
7	Minimize chance for dry matter loss > 0.5 (ratio)
8	Minimize cost of overdrying ($/t)
9	Minimize cost of energy usage (kWh/t)
10	Minimize net cost

[a] Sources: Lynch and Morey (1989); Peart et al (1985); Pertech, Inc., Chaska, MN.

The control strategy employed by an in-bin controller to realize a criterion in Table I can vary greatly. As the listing of 23 different fan or heater control strategies in Table II suggests, a variety of opinions exists among in-bin controller manufacturers and investigators on how best to control the fan or heater operation of an in-bin drying or aeration system. Except for three optimization techniques (strategies 11–13 in Table II), the in-bin open-loop drying and aeration strategies are heuristic in nature, since they consist of a set of simple rules based on operator experience.

TABLE II
Fan or Heater Control Strategies for In-Bin Drying or Aeration of Grain[a]

Strategy Number	Strategy
1	Continuous fan operation with or without supplemental heat
2	Humidistat control of upper relative humidity (rh) limit
3	Humidistat control of lower and upper rh limits
4	Fan operation based on the equilibrium moisture content (EMC) of the grain and on a self-adjusting minimum number of hours of daily fan operation, which depends on the calendar date
5	Humidistat control of a variable upper rh limit, which depends on the varying maximum moisture content (MC) of the bin
6	Humidistat control of a variable upper rh limit, which depends on the varying maximum bin MC, and of a variable lower rh limit, which depends on the varying minimum bin MC
7	Fan operation based on the grain EMC and on a self-adjusting minimum number of hours of daily fan operation, which depends on the maximum bin MC
8	Continuous fan operation followed by fan operation based on the upper and lower EMCs of the grain
9	Continuous fan operation until reaching a predetermined MC in the top of the bin, followed by operation based on the upper and lower MCs of the grain
10	Time clock control of fan operation and/or heater
11	Fan operation based on the critical path method of optimization
12	Fan operation and airflow rate based on the dynamic programming method of optimization
13	Fan and heater operation based on a two-step method of optimization (Ryniecki's method)
14	Fan operation based on the estimated drying rate and dry matter loss
15	Fan operation based on the difference of drying and exhaust air temperatures
16	Fan operation based on the difference between the temperature of the drying air and the maximum grain temperature
17	Fan operation based on the estimated MC of the grain
18	Fan operation based on the estimated dry matter loss of the bin-surface layer
19	Fan operation, plus supplemental heat addition, based on the plenum rh and bin exhaust air temperature
20	Fan operation according to a localized control strategy; e.g., for Ontario in-bin drying corn: 1) continuous fan operation for a set time without supplemental heat, 2) final drying (using supplemental heat) with humidistat control of lower and upper rh limits, and 3) interruption of the final drying process if the maximum bin MC is less than a preset value
21	Fan operation based on a 3–5% EMC window initially and on a smaller EMC window near the end of the drying cycle; the maximum number of days between fan operation is adjusted automatically; a hotspot override protects grain from overheating.
22	Same as 21, plus an additional 5–10°C temperature window with a limit on the maximum and minimum temperatures
23	Fan and heater operation based on predicted weather conditions

[a] Sources: Brook (1987); Colliver et al (1983); Gunasekaran and Shove (1986); Kelley et al (1990); Lynch and Morey (1989); Mittal and Otten (1983); Peart et al (1985); Pertech, Inc., Chaska, MN; Ryniecki and Nellist (1991); Sentry Technologies, Inc., Chanhassen, MN.

The reader is referred to the cited references to obtain a detailed description of the strategies and performance indices that have been investigated. In this article it is possible to discuss only a limited number of investigations.

Of the 10 objective criteria listed in Table I, three performance indices seem to have been used most frequently to evaluate a fan or heater control strategy for in-bin drying or aeration: 1) dry matter loss, 2) energy consumption, and 3) overdrying. Of the 23 fan or heater control strategies tabulated in Table II, strategies 2 (upper limit), 3 (upper and lower limits), 4 (self-adjusting equilibrium moisture content [EMC]), 21 (contracting EMC window), and 22 (EMC and temperature window), or variations thereof, are presently employed on commercial in-bin controllers.

Control Results

The simulation study by Lynch and Morey (1989) is used to illustrate the effect of fan or heater control of in-bin drying under Minnesota conditions. This study considered the fall or spring drying of 20% wb corn in a 4.85 m deep bin to 14% wb at an airflow rate of 1.1 $m^3 \cdot mi^{-1} t^{-1}$, with a plenum air temperature rise of 1.1°C due to fan operation. Control strategies 1–9 in Table II were analyzed; the average results of four strategies for a 23-year period are given in Table III. It is striking that the advantages of the complicated fan control strategies are relatively modest compared to those of continuous fan operation. Of the four strategies, number 4 (the self-adjusting EMC band strategy) appears to offer the best overall results; it is the strategy employed in one of the commercial controllers (Sentry Technologies, Inc.).

In addition to the study of Lynch and Morey (1989), several other investigations merit attention. Brook (1987) considered both fan and heater control for the in-bin drying of wheat under U.K. conditions; the control of both the fan and the heater was based on the expected drying rate and spoilage rate. Although the control strategy is novel, Brook's results do not appear to offer major advantages over upper and lower limit control.

A different approach to the in-bin control problem was considered by Gunasekaran and Shove (1986). Instead of employing intermittent fan and heater operation, they varied the daily airflow rate so that the energy use was minimized; the selection of the flow rate was based on dynamic programming. An energy savings of 15% was obtained as compared to continuous fan operation. Similar results were observed by Colliver et al (1983), who employed the critical path method of optimization in evaluating the management of low-temperature grain drying. The control criterion of Colliver et al (1983) was compared to several in-bin control strategies, including a "localized" control algorithm, by Mittal and Otten (1983); the results show a definite advantage (i.e., in the range of 10–15%) in energy consumption and dry matter deterioration for the "localized" strategy compared to other control measures.

Ryniecki and Nellist (1991) presented an optimum control strategy for a low-temperature grain drying system. Their strategy was tested by simulation of a 3 m deep bed of wheat, initially at 20% moisture content and operating over 20 years under U.K. conditions. The results showed significant reduction in drying costs, with savings of 34% in energy consumption compared to that from conventional policies. In Ryniecki and Nellist's strategy, the airflow was altered between heating and nonheating periods, and the control setpoint relative humidity varied with the progress of drying. Although the results showed some advantages, the optimization method is complex and requires much computation time (about one week on a Vax computer).

Of the older simulation studies on in-bin dryer control, two warrant attention. Pfost et al (1977) compared several clock and humidistat fan controllers for the in-bin ambient air drying of corn. They concluded that in-bin controllers can lead to reduced energy requirements but increased dry matter loss compared to those from continuous fan operation. Morey et al (1979) considered continuous fan operation for in-bin corn drying; they advised against the use of management strategies involving turning off the fan based on the timeclock or on the relative humidity or temperature of the ambient air. The oppositeness of the views of these investigators is mainly due to the unequal conditions under which the strategies were tested. It provides a lesson: the results of a control strategy for in-bin grain drying or aeration are location dependent and cannot be generalized.

CONTINUOUS-FLOW GRAIN DRYER CONTROLS

The moisture content of wet grain reaching a high-temperature continuous-flow dryer over a 24-hr 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 corn 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. Figure 1 shows an example of overdrying corn in a commercial crossflow dryer managed intuitively by an experienced operator. The manual control decisions in changing the auger speed are based on hourly readings of the inlet and outlet moisture contents of the grain. The operator succeeded in keeping the average outlet moisture content to within 0.9% of the setpoint.

Automatic control of continuous-flow dryers is usually designed to minimize the overdrying or underdrying of the grain. Secondary objectives are minimizing energy consumption and optimizing dryer capacity, both necessarily subject to grain quality constraints.

For many years, the automatic control of continuous-flow grain dryers was limited to temperature-activated feedback-type controllers that measure the grain or the exhaust-air temperature

TABLE III
Results of the In-Bin Drying of 20% MC[a] Corn Under Different Control Strategies and Minnesota (USA) Conditions[b]

	Control Strategy[c]			
Drying Rate	**1**	**3**	**4**	**6**
Change in fan operation,[d] %	···	−9.5	−12.3	−13.3
Overdrying from 14.5% average, %	0.5	0.6	0.5	0.2
MC range, %	2.6	2.8	2.4	1.9
Average DML,[e] %	0.18	0.17	0.17	0.20
Maximum DML, %	0.28	0.29	0.28	0.35
Change for DML > 0.5%, %	0	0	4.5	4.5
Net savings,[d] $/t	···	0.51	0.56	0.84

[a] Moisture content.
[b] Adapted from Lynch and Morey (1989).
[c] Refer to Table II for a description of the control strategies.
[d] Compared to control strategy 1 (continuous fan operation).
[e] Dry matter loss.

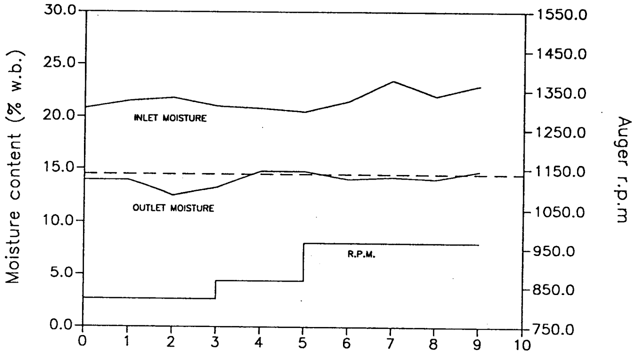

Fig. 1. A continuous-flow grain dryer operating under manual control. Dashed line shows the setpoint. (Adapted from Eltigani and Bakker-Arkema 1987)

at one or several locations along the drying column. A temperature-activated controller may be useful on a farm dryer. However, this type of controller is inaccurate and inconsistent at moisture content changes exceeding ±3%, due to the nonlinearity of the drying process and the lack of a reliable functional relationship between the exhaust-air temperature and the outlet moisture content. Therefore, the temperature-activated controllers are slowly being replaced by moisture-activated systems, especially on the continuous-flow dryers operating at commercial elevators.

Control systems for continuous-flow dryers are more expensive than those for in-bin dryers. They require considerable computer power and sophisticated instrumentation for moisture measurement. Therefore, the cost is substantial ($20,000–30,000 in U.S. dollars [as of December 1990]).

The automatic controllers for continuous-flow grain dryers that are discussed below fall into five categories: 1) classical feedback control, 2) optimal feedback control, 3) feedforward control, 4) adaptive control, and 5) expert (fuzzy) control.

Classical Feedback Control

The block diagram in Figure 2 represents the classical closed-loop proportional and integral (PI) feedback control of a continuous-flow grain dryer (Marchant 1985). The grain flow rate at time t, $V(t)$, is based on the error between the output and setpoint of the controlled variable, $e(t)$, according to the standard continuous PI control algorithm:

$$V(t) = K\Big[e(t) + \frac{1}{T_i}\int e(t)dt\Big] + V(o)\,, \qquad (1)$$

where $V(o)$ is the initial flow rate of the grain, K is the proportional gain, and T_i is the integral time constant. The controlled variable can be the exhaust air temperature or the outlet grain moisture content. The proportional term in equation 1 provides the rapid response to an error, and the integral term prevents a steady-state error.

Whitfield (1986) tested the classical PI control algorithm (eq. 1) by simulation for a concurrent-flow grain dryer after determining the "best" values for the parameters K and T_i. It was noted that the best parameter values for a sudden increase in the inlet moisture content are different from those for a sudden decrease; also, that the best K and T_i values depend on the amount of drying that is required. Thus, the classical PI algorithm functions well in a limited initial moisture range but results in oscillations outside of this range (see Fig. 3). The direct cause of the instability is the nonlinear relationship between the grain flow rate and the drying rate.

To overcome the nonlinear nature of the drying process with respect to time, Whitfield (1988a) designed a digital PI controller based on the following control algorithm:

$$u(t) = K[x(t) - ax(t-1)] + u(t-1) \qquad (2)$$

where

$$u(t) = [1/V(t)]\,, \qquad (3)$$

$$x(t) = \log M(t) - \log M(\text{setpoint})\,, \qquad (4)$$

M is moisture content, K is the gain, and a the zero position. The variables u and x were chosen in equation 2 because they can approximately be considered to represent two linearized variables in the continuous-flow drying process.

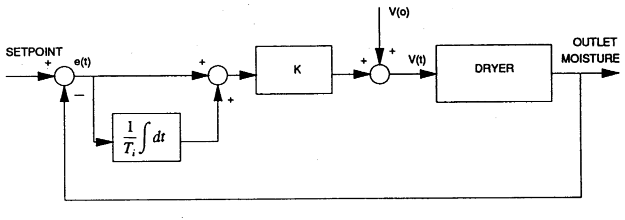

Fig. 2. Block diagram of proportional and integral control of continuous flow grain dryers. See equation 1 in text. (Adapted from Whitfield 1986)

After determining and tuning the parameter values K and a in equation 2, Whitfield (1988b) experimentally tested the PI control algorithm of equation 2 on a mixed-flow dryer. The feedback controller gave a fairly rapid response to a change in inlet moisture content, showed less oscillation than the PI controller of equation 1, especially during start-up, and appeared to be stable over a wide inlet moisture content range.

Conventional feedback controllers require tuning of the parameters to fixed values by an operator. This process is time-consuming. The response of these controllers, as is the case for all feedback control, is slow when the residence time of the grain in the dryer is long. For these reasons, the authors do not expect traditional feedback controllers to become popular for continuous-flow grain dryers.

Optimal Feedback Control

The earliest attempts for computer control of continuous-flow grain dryers were based on optimal feedback control (Holtman and Zachariah 1969). The technique requires the minimizing (or maximizing) of an objective function F. For a dryer:

$$\min F = \min\Big[\int[M(t) - M(\text{setpoint})]^2 dt\Big]\,. \qquad (5)$$

To calculate the optimum value of the grain flow rate, optimal control requires a simple process model that approximates the drying process. For linear process control, the following equation is adequate:

$$M(t) = M(o) - At\,, \qquad (6)$$

where A is a linear drying constant. Holtman and Zachariah (1969) employed equation 6 to minimize equation 5 by quadratic programming for the operation of a crossflow dryer.

Although optimal feedback control is able to precisely control a continuous-flow dryer, the large computational requirement and the difficulty in mathematically defining an objective function make future commercial application of the technique unlikely.

Feedforward Control

A feedforward controller measures continuously or intermittently the main load variable (i.e., the inlet moisture content) in a continuous-flow grain dryer. Subsequently, a process model computes the residence time for which the grain should remain

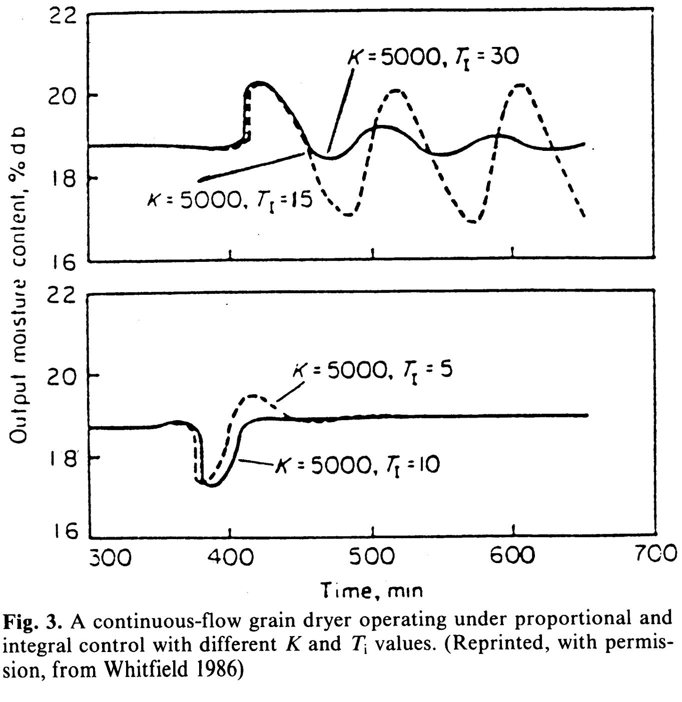

Fig. 3. A continuous-flow grain dryer operating under proportional and integral control with different K and T_i values. (Reprinted, with permission, from Whitfield 1986)

in the dryer. If a correction of the residence time is required due to a change in the inlet moisture content, corrective action is taken at the moment the grain enters the drying section. Thus, no time delay is encountered with feedforward control, in contrast to feedback control, which has an inherent 0.5–2.5 hr dead time on a continuous-flow grain dryer.

Feedforward requires a dynamic drying model that can rapidly calculate the required correction in the speed of the metering rolls when the inlet moisture content changes. Nonsteady state differential-equation (DE) simulation models have been developed for concurrent-flow dryers (Moreira and Bakker-Arkema 1990c), for crossflow dryers (Eltigani 1987), and for mixed-flow dryers (Bruce 1986). These DE models do not fulflll the essential requirement of rapid computer solution. However, the DE models have been used to develop empirical process models that adequately simulate the three dryer types (Moreira 1989). (In the following equations, *B, C,* and *D* represent the process model parameter values of a particular dryer.) The process model can be a simple one-parameter exponential equation (Forbes et al 1984):

$$M(t) = M(\mathrm{o})[\exp(-Bt)]\,. \qquad (7)$$

Or it can be a two-parameter linear equation (Eltigani and Bakker-Arkema 1987):

$$M(t) = M(\mathrm{o})(C_1 + C_2 t)\,. \qquad (8)$$

Or it can be a two-parameter linear difference equation (Moreira and Bakker-Arkema 1990a):

$$M(t) = D_1 T_r(t-1) + D_2 M(t-\tau) + [N(t)/\Delta]\,, \qquad (9)$$

where T_r is the grain residence time, $N(t)$ is unmeasurable white noise, τ is the feedforward time delay, and Δ is the differential operator.

Feedforward control of continuous-flow grain dryers has been implemented in conjunction with adaptive control.

Adaptive Control

In classical feedback and feedforward control, the parameters in the control law and in the process model are fixed. Thus, the values of K and T_i in equation 1 and of C_1 and C_2 in equation 8 are identified for a certain dryer design and grain type, and they remain unchanged during the dryer operation. Due to the frequently changing environmental and grain-property conditions, this may lead to inadequate control of the outlet moisture content. Adaptive feedback and feedforward control provides for the recursive tuning of the control or model parameters during the drying process.

Forbes et al (1984) employed an adaptive feedforward moisture-activated controller on a crossflow grain dryer; the drying was simulated by an exponential decay-type process model (i.e., equation 7). The model parameter B was intermittently modified by linear filtering, thereby providing indirect feedback control. The model-based feedforward controller used a pseudoinlet moisture in the process model as the moisture content term, with the pseudomoisture content representing the initial moisture content of all grain presently in the dryer. The Forbes et al study became the basis for a successful commercial dryer controller (Rolfes Agri-Industrial Canada Inc., Waterloo, Ontario). Figure 4 is an example of the inlet and output moisture contents of a crossflow dryer controlled by the Rolfes adaptive feedforward controller; good control is obtained.

Adaptive model-based feedforward control was also the basis for the controller developed by Eltigani and Bakker-Arkema (1987). The dryer dynamics are modeled with a two-term linear process model (i.e., equation 6), and the model parameters C_1 and C_2 are estimated by the sequential least square method. The control software was incorporated into a commercial controller (Shivvers, Inc., Corydon, IA), which tests the inlet and outlet moisture contents intermittently (i.e., every 3–5 min). Figure 5 is a schematic of the Shivvers automatic control system; Figure 6 illustrates the control obtained with a commercial crossflow grain dryer.

Nybrant (1988) tested an adaptive feedback temperature-activated controller on a crossflow dryer; a pole-placement control strategy was employed (Tuffs and Clarke 1985). The controller reacted well to sudden inlet moisture changes, but the response was slow compared to that of the Rolfes and the Shivvers feedforward controllers. Nybrant employed temperature as the control variable; replacing temperature by moisture content would likely improve the control action of the controller.

Moreira (1989) combined the advantages of the Rolfes/Shivvers and the Nybrant controllers and designed an adaptive feedforward and feedback controller for crossflow dryers (Moreira and Bakker-Arkema 1990a) and for multistage concurrent-flow dryers (Moreira and Bakker-Arkema 1990b). The software was installed into a moisture-based Shivvers controller. (Figure 7 shows the block diagram of the adaptive controller.) The control software contains a linear-difference model and a modified pole-placement control algorithm (Nybrant 1986). Figure 8 illustrates the results of the control of a crossflow corn dryer; good control is obtained even for sharp changes in the inlet moisture content.

Expert (Fuzzy) Control

In cases where the objective of a control action is difficult to express in equation form, classical or adaptive control may not provide the desired result. An example is the maintenance

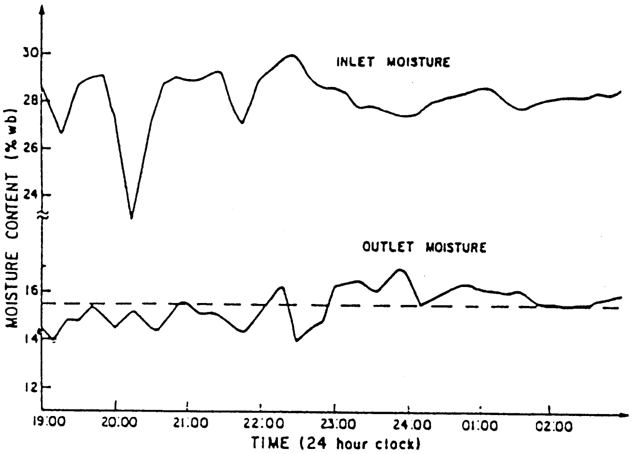

Fig. 4. A continuous-flow grain dryer operating under feedforward control. Dashed line shows the setpoint. (Reprinted, with permission, from Forbes et al 1984)

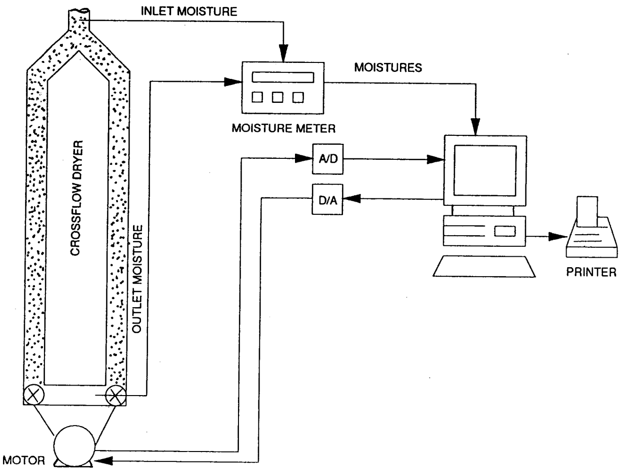

Fig. 5. Schematic of an automatic control system for continuous-flow grain dryers. A/D = analog to digital, D/A = digital to analog. (Adapted from Moreira 1989)

of grain quality during the continuous-flow drying process. Many factors affect grain quality, including drying rate, grain maturity, grain variety, and grain moisture. Traditional control systems do not consider this range of control parameters, and thus the use of fuzzy control may be beneficial (Gui et al 1988).

Fuzzy, or expert, control employs a set of heuristic rules under which a process such as grain drying should operate. This implies that the control rules are mainly based on experimental knowledge and operator experience.

Zhang et al (1990) simulated a prototype fuzzy control system in conjunction with a crossflow corn dryer. Breakage susceptibility was selected as the control variable. A table was created for weighting the effects of drying temperature, initial moisture content, and EMC on the breakage susceptibility. Also, a set of heuristic control actions was established with the associated confidence factors. The fuzzy controller minimized the drying temperature to 50°C to minimize the breakage susceptibility. A more sophisticated weighting table of the manipulated variables should also consider the constraints on the values of the variables.

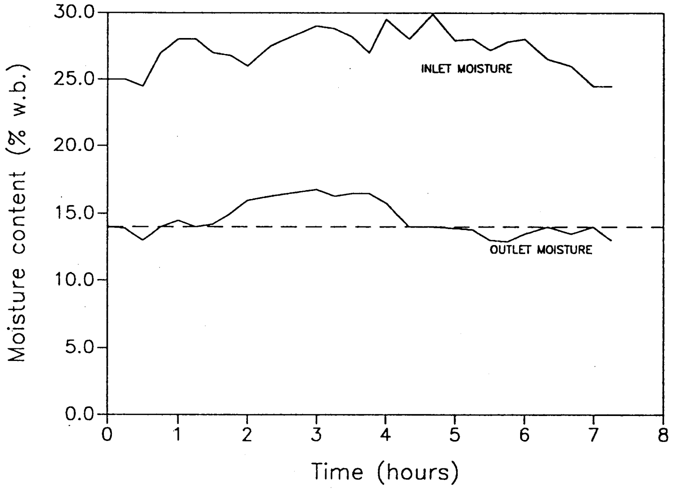

Fig. 6. A continuous-flow grain dryer operating under feedforward control. Dashed line shows the setpoint. (Adapted from Eltigani and Bakker-Arkema 1987)

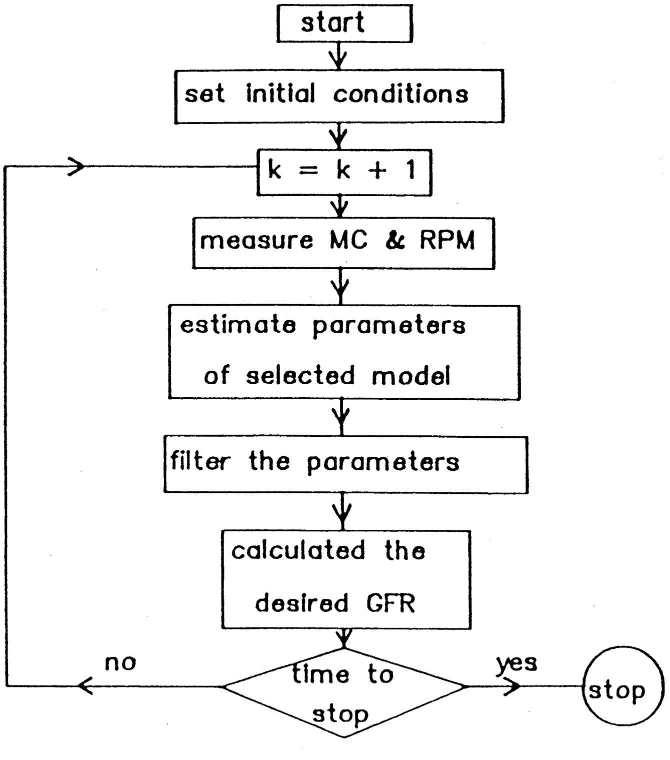

Fig. 7. Control algorithm for continuous-flow grain dryers. MC = moisture content, RPM = revolutions per minute, GFR = grain flow rate. (Reprinted, with permission, from Moreira 1989)

Fuzzy control of continuous-flow grain dryers has not yet been commercialized. Sufficient experience has not yet been gained to judge this controller type.

Control Quality

In the previous sections five controller types have been presented. What is still missing is a quantification of the success or failure of a particular control system.

Douglas et al (*in press*) proposed two measures, QM_1 and QM_2, for evaluating the quality of control. QM_1 is defined as the ratio of the outlet moisture standard deviation without control (S^*_{out}) to that with control (S_{out}), or

$$QM_1 = S^*_{out}/S_{out} . \quad (10)$$

QM_1 is a measure of the improvement in the moisture variation over no control. A large value of QM_1 is thus desirable.

The second measure of the quality of a controller, QM_2, is defined as the ratio of an acceptable percentage of off-specification product (OS_{accept}) to the actual percentage of that material (OS_{actual}):

$$QM_2 = OS_{accept}/OS_{actual} . \quad (11)$$

Table IV shows a comparison of the control quality of three crossflow dryers under manual control, temperature-based feedback control, and moisture-based feedforward control. Clearly, the moisture-based feedforward controller best controlled the crossflow dryer, at least according to the QM_1 and QM_2 criteria.

CONCLUSIONS

Dryer control is an active area of investigation. In the past decade, important technological progress was made in the automatic control of in-bin and continuous-flow dryers. Both controller types are based on microprocessor technology, and each of several are commercially available.

Installing automatic controls on a grain dryer has definite advantages with respect to grain quality and operating costs. In addition, less operator expertise is required for automatically controlled than for manually controlled systems, and less shrinkage occurs.

In-bin control usually operates under a heuristic control strategy. The temperature and humidity of the ambient air and the grain are measured, and the fan and heater are turned on

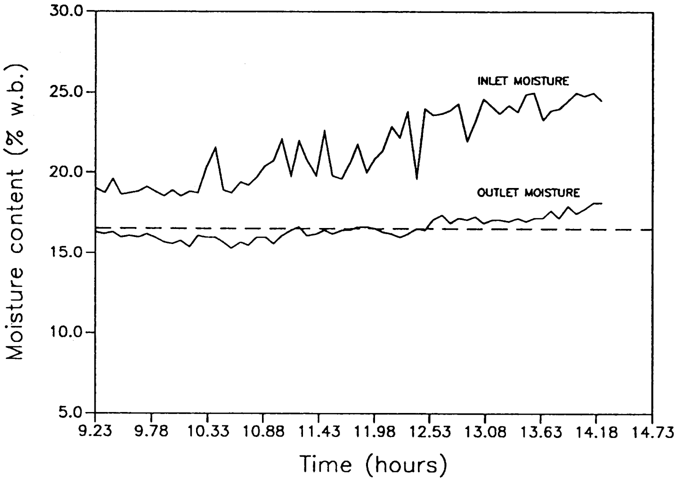

Fig. 8. A continuous-flow grain dryer operating under adaptive feedforward/feedback control. Dashed line shows the setpoint. (Adapted from Moreira and Bakker-Arkema 1990a)

TABLE IV
Quality Control Quantification of Three Crossflow Dryers

	Criteria[a]				
Control Type	S_{in}	S^*_{out}	S_{out}	QM_1	QM_2
Manual	1.37	0.90	0.55	1.63	0.76
Temperature-based feedback	0.62	0.44	0.55	0.80	0.89
Moisture-based feedforward	3.14	1.85	0.71	2.61	2.24

[a] S_{in} = standard deviation of the inlet moisture content, S_{out} = standard deviation of the outlet moisture content with control, S^*_{out} = standard deviation of the outlet moisture content without control. $QM_1 = S^*_{out}/S_{out}$. $QM_2 = OS_{accept}/OS_{actual}$, where OS_{accept} = acceptable percentage of off-specification product, and OS_{actual} = actual percentage of off-specification product.

and off according to a specific set of rules. Since little computing power is required, and the software and hardware are relatively simple, the cost of this type of in-bin control system is moderate.

In-bin control strategy based on optimization techniques can result in energy savings as high as 34% as compared to the energy required by heuristic policies. This strategy requires higher computing power, and the software and hardware are more complicated than those based on the heuristic approach.

Continuous-flow dryer control is either 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. Optimal feedback control systems require a well-defined objective function, which is difficult to obtain mathematically. Classical feedforward controllers need an accurate dynamic model of the drying process, which requires long computation time for on-line calculations.

An adaptive controller has been shown to offer the best technique for adequately controlling continuous-flow grain drying. Adaptive feedback and feedforward control is able to minimize 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. This control has not yet been commercialized.

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.

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 substantial.

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

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