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Abstract. *A computer model was validated with experimental data and used to evaluate the performance of a new in-bin counterflow corn drying system. The recent commercial availability of the new system utilizes a leveling auger that moreprecisely regulates the bed depth. Drying air temperature, initial and final moisture, bed depth, bin diameter, and fan power affected drying capacity and specific energy consumption. Optimal bed depth is critical; given a particular 9.7 kW (13 hp) vane-axial fan, the optimal depth in a 5.5 m (18 ft) diameter bin is 1.5 m (4.9 ft), and the optimal depth in a 9.1 m (30 ft) bin is 0.8 m (2.6 ft). For the same fan, optimal bed depth corresponded to an airflow of 11.1 m^3/min/t (10 cfm/bu), regardless of bin diameter.* **Keywords.** *Corn, Drying.*

About 60% of the total energy required in corn production is used for drying (Brooker et al., 1992). Because up to 80% of the artificial drying of corn in some states is on-farm (ICLRS, 1984), drying techniques used by farmers are of utmost importance with respect to energy consumption. The drying technique considered in this study is heated-air, in-bin counterflow drying. It is a combination-drying technique, because the corn is usually transferred to a separate bin for dryeration. In-bin counterflow drying typically requires 40% less energy than high-temperature automatic batch drying (Kalchik et al., 1979). This technique also compares favorably, in terms of energy efficiency, with other on-farm drying methods (Kalchik et al., 1979).

Figure 1 shows the configuration of a new in-bin counterflow drying system. Wet grain is loaded into the drying bin, while hot air is forced upward through the perforated floor. A moisture content sensor in the center of the bin, above the false floor and sweep auger, controls the auger activation. The auger has a flighting that is tapered from a larger diameter at the bin center to a smaller diameter near the bin wall. When activated, the auger makes one complete sweep around the bin in approximately 20 to 25 min, removing a layer of dried corn 13 to 18 cm (5 to 7 in.) thick. The wet grain above moves down, and the process is repeated. Consequently, the system can be labeled more exactly as an in-bin intermittent counterflow dryer. Recently, a leveling auger became commercially available which adds an even layer of wet grain on top of the grain bed. A controller can be used to maintain a fixed bed depth or to allow the depth to vary with the harvest rate (by allowing the leveling auger to float). Because operators of in-bin counterflow drying systems can now better control bed depth, it is important to understand how various system parameters affect the optimal drying depth.

In-bin counterflow drying systems have three different modes of operation. The first mode, examined thoroughly by Roberts and Brooker (1975), is recirculation drying, a batch configuration. In this mode, grain that is removed from the bottom layer is redistributed on top of the pile, instead of transferred to a different bin. Roberts and Brooker (1975) investigated the moisture profile within the bed in order to determine whether the dried corn rewets

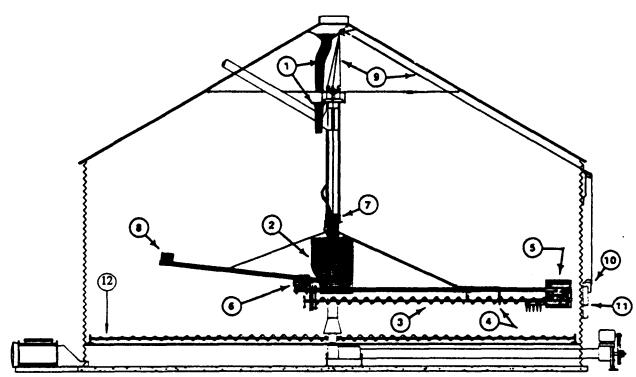

Figure 1–Schematic of the in-bin counterflow drying system with the new leveling auger. 1) Funnel directs incoming wet grain. 2) Collecting hopper rotates and directs grain to leveling auger. 3) Auger leveling grain surface. 4) Switch detects grain level. 5) Self-adjusting drag controls auger motion. 6) Electric motor powers leveling auger. 7) Commutator ring transfers electric current to the motor. 8) Counter balance offsets auger weight. 9) Suspension cable supports auger weight. 10) Electric winch raises and lowers leveling auger. 11) Control panel controls leveling auger. 12) Sweep auger. Source: Shivvers, Inc. (1992).

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Trade names are used in this study solely to provide specific information. Mention of a trade name does not constitute a warranty of the product by the authors nor by Purdue University nor by Michigan State University, nor an endorsement of the product to the exclusion of other products not mentioned.

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after it is spread on top of the bed. By using mathematical and experimental analysis, they determined that the entire bed dries after one complete recirculation cycle. Although some rewetting occurs, the net effect is negligible.

The second mode of operation is batch counterflow. The system is identical to that used for recirculation batch drying, except that the dried layer of grain is removed to a separate bin for dryeration. The grain depth thus decreases with each sweep of the auger. The process begins as soon as the bin is filled to an initial depth with wet grain and continues until the bin is empty.

The third mode of operation is continuous counterflow drying. This mode differs from the batch counterflow method in that a continuous supply of wet grain is used to refill the bin as dry grain is removed from the bottom. The process of refilling can be regulated to correspond with the removal of dry grain, or it can be irregular so that it accommodates variations in harvesting rate. In order to precisely regulate the bed depth, a wet holding bin is necessary. The Midwest Plan Service (MWPS, 1988) recommends an optimal bed depth of 0.9 to 2.7 m (3 to 9 ft).

Bridges et al. (1983) used a computer model to evaluate the performance of an in-bin continuous counterflow drying system. Fan and bin requirements were estimated to achieve desired drying capacities for given initial and final moisture contents. The effect of loading rate on drying capacity for a system in which bed depth varied with time was also evaluated. Bridges et al. (1984) used the same model to predict maximum drying rates and energy consumption for a range of operating parameters. The optimal drying depth (based on only maximum drying capacity) varied with the operating parameters and ranged between 0.6 m and 1.2 m (2 to 4 ft). However, the effect of various operating parameters on optimal depth was not reported.

The specific objective of this project was to utilize a simulation model to investigate the effects of drying air temperature, initial and final moisture contents, bed depth, bin diameter, and fan power on the optimal bed depth for the new in-bin counterflow drying system.

Methods

Experimental

Experimental data were collected on a research farm near Bellaire, Michigan (Mwaura, 1984). The in-bin counterflow drying system consisted of a 5.5-m (18-ft) diameter steel bin with a 9.7 kW (13 hp) fan and a 1070 kW (3.65×10^6 Btu/h) heater. The bin was equipped with a tapered sweep auger system for removing an even layer of grain from the bottom of the bed; however, the experimental data were collected prior to the development of the leveling auger system. The drying system was manufactured by Shivvers, Inc., Corydon, Iowa.

Analysis

A computer model developed for the in-bin counterflow drying process was used to obtain simulated performance data in this study. The model consists of four partial differential equations. It is a modified version of the Michigan State University (MSU) fixed bed model, which has been previously described (Bakker-Arkema et al., 1974; Brooker et al., 1992). One of the four partial differential equations is a thin-layer drying equation. The thin-layer equation used was given in Troeger and Hukill (1970) and is valid for temperatures between 26.7 and 71.1° C (80 to 160° F). The empirical Kalchik equation was used to calculate equilibrium moisture content (Kalchik et al., 1979).

For the in-bin counterflow system, the MSU fixed bed model was modified to account for the reduction of grain depth in the bin by a discrete distance after each cycle of grain removal. This intermittent process was modeled by shifting the known conditions of the corn downward in the simulated bed by a distance equal to the thickness of the removed layer of dried corn. The removal of dried corn and addition of wet corn was assumed to be an instantaneous process. Because of the recent development of the leveling auger system, only continuous drying with a fixed bed depth was examined. Batch counterflow drying performance was previously evaluated by Marks et al. (1988).

The drying system was simulated for greater than 24 h, in order to achieve steady, continuous operation. During each simulation run, the inlet grain and air properties were held constant. The fan simulation was based on the characteristic fan curve provided by the manufacturer (Parkes, 1982). The drying capacity and specific energy consumption for each simulation run were calculated by averaging these values from the last five cycles between auger sweeps.

Results and Discussion

Validation

Table 1 compares the experimental and simulated performance data for a typical batch counterflow system. Because the experimental data were collected prior to the availability of the leveling auger system, continuous leveling and moisture-triggered, automatic refilling were not available. Because of these limitations in the experimental data, a batch counterflow example was chosen for comparison. Even though the model will subsequently be used to model refill counterflow, this comparison shows that the intermittent counterflow aspect

Table 1. Comparison of experimental and simulated performance for a batch counterflow corn drying system, with a 9.7 kW (13 hp) vane-axial fan

Cycle	Cycle Time (h)		Bed Depth	Moisture (% w.b.)		Airflow ($m^3/min/m^2$)	
No.	Exper.	Simul.	(m)	Exper.	Simul.	Exper.	Simul.
1	1.80	1.48	1.8	18.9	18.5	12.0	11.9
2	0.53	0.62	1.7	n/a*	18.4	12.4	12.2
3	0.62	0.81	1.5	18.9	18.4	12.7	12.4
4	0.77	0.79	1.4	18.6	18.7	12.9	12.6
5	0.77	0.98	1.2	n/a*	18.4	13.2	12.9
6	0.85	0.58	1.0	n/a*	18.7	13.5	13.2
Total	5.34	5.26					

* n/a = data not available.
Average drying temperature: 77.0° C
Initial grain depth: 2.0 m
Average ambient temperature: 12.4° C
Average ambient relative humidity: 84.0%
Initial grain moisture content: 26.2% w.b.

of the model successfully simulates the process. For six cycles of drying, the total simulated drying time was only 1.5% less than the experimental drying time. The maximum difference between experimental and simulated airflow was 2.4%, and the outlet moisture content was closely matched during the simulation. For refill counterflow drying, the model simply simulates the refilling process by adding a new layer of wet grain on top of the pile. On the basis of these results, the model was assumed to be a valid tool for evaluating system performance.

Simulation Results

Figure 2 shows the system response during a representative run of continuous counterflow operation. After approximately five hours, the average grain temperature and moisture achieved steady-state. Slight increases in average moisture content and slight decreases in average grain temperature at certain times were caused by the addition of cool wet grain to the bin. Over time, the in-bin counterflow dryer equipped with a controlled leveling auger functions as a steady, continuous dryer. For all of the simulation runs, constant ambient conditions of 10° C (50° F) and 70% relative humidity were used.

Figure 3 shows the effect of drying air temperature on drying capacity and specific energy consumption (SECO) for two different moisture reduction ranges in a 5.5-m (18-ft) diameter bin with a 9.7-kW (13-hp) axial fan. The drying bed depth was 2 m (6.6 ft). Airflow was 7.5 m^3/min/t (6.8 cfm/bu). Drying air temperatures from 32.2° C (90° F) to 71.1° C (160° F) were considered. For a drying range of 22 to 17% w.b. moisture content, an increase in temperature from 32.2° C to 71.1° C results in a capacity increase of approximately 115%, from 2.0 t/h (79 bu/h, assuming 56 lb/bu) to 4.3 t/h (169 bu/h). For a drying range of 25 to 16.5% w.b., the same temperature increase results in a capacity increase of approximately 208%, from 1.2 t/h (47 bu/h) to 3.7 t/h (145 bu/h). In both cases, the capacity increase is nearly linear with temperature. However, the specific energy consumption (i.e., energy used per mass of water removed) remains nearly constant across the entire temperature range. Removal of less water at the same drying temperature results in a higher specific energy consumption. Therefore, the SECO for the 22 to 17% w.b. range is greater than the SECO for the 25 to 16.5% w.b. range. The results shown in figure 3 imply that high drying temperatures increase throughput of the in-bin counterflow system without significantly affecting energy consumption. An important consideration, however, when increasing the drying air temperature must also be the effect of higher grain temperatures on grain quality.

Figure 4 shows the effect of bed depth on drying capacity and SECO for two moisture reduction ranges for the same fan-bin combination. Airflow varied with bed depth. The drying air temperature was 71.1° C (160° F), and the bin diameter was 5.5 m (18 ft). The drying capacity curves show that, for both drying ranges, the maximum capacity occurred at a depth of approximately 1.5 m (4.9 ft). This implies that the difference between initial and final moisture does not significantly affect the optimal depth. At the 1.5-m depth, the SECO is slightly above its

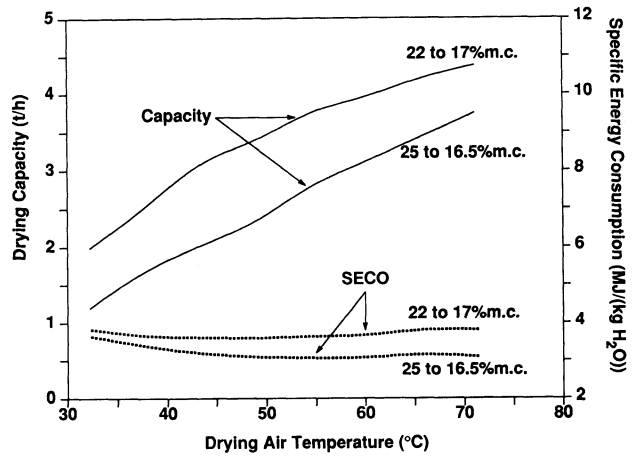

Figure 3–Drying capacity and specific energy consumption (SECO) vs. drying air temperature for two moisture reduction ranges. Bin diameter 5.5 m. Airflow 7.5 m^3/min/t. 9.7 kW axial fan. Bed depth 2 m. Drying corn from 25 to 16.5.% w.b. moisture. Each curve represents seven simulation runs.

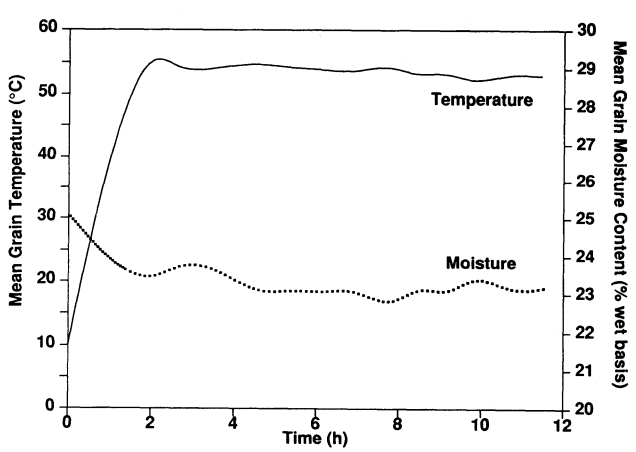

Figure 2–Average corn temperature and average corn moisture content in bed vs. time. Bin diameter 5.5 m. Drying corn from 25 to 16.5% w.b. moisture. Drying air temperature 71.1° C.

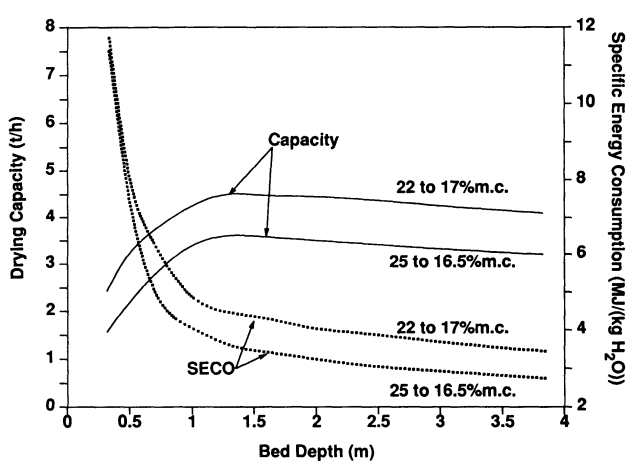

Figure 4–Drying capacity and specific energy consumption (SECO) vs. bed depth for two moisture reduction ranges. Bin diameter 5.5 m. 9.7 kW axial fan. Drying air temperature 71.1° C. Each curve represents 13 simulation runs.

minimum. Decreasing the bed depth from 1.5 m (4.9 ft) to 1.2 m (3.9 ft) does not increase capacity significantly, but the SECO does increase. Below 1.2 m, the capacity decreases significantly with decreasing depth, while the SECO increases significantly. For these shallow depths, the exit air above the bed is not saturated, and its drying potential is wasted. For both moisture removal ranges, increasing the bed depth from 1.5 m (4.9 ft) to 3.8 m (12.5 ft) results in approximately 18% reduction in specific energy consumption and approximately 10% reduction in drying capacity. Therefore, if maximizing capacity with nearly minimum SECO is the primary criterion for optimal performance, the leveling auger of this system configuration should be operated at a depth of approximately 1.5 m.

Allowing the bed depth to fluctuate between 1.5 m and 3.8 m (4.9 to 12.5 ft) (i.e., if no wet holding bin is available) might be an acceptable operating strategy. Drying capacity would remain near maximum, while SECO would be near minimum. Also, the additional investment in a wet-holding bin would not be required.

Figure 5 shows the effect of bed depth and drying air temperature on drying capacity and specific energy consumption. The simulations were for a 7.3 m (24 ft) diameter bin, with a 9.7-kW (13-hp) axial fan, and the initial and final moistures were 25 and 16.5% w.b., respectively. For both drying air temperatures, the maximum drying capacity is achieved at a bed depth of approximately 1.1 m (3.6 ft). This indicates that drying air temperature does not significantly affect the optimal bed depth. By increasing bed depth from 1.1 m (3.6 ft) to 3.8 m (12.6 ft), capacity is reduced approximately 13%, and SECO is reduced approximately 19%. Interestingly, there is negligible effect of drying air temperature on SECO beyond the optimum bed depth (see fig. 3).

Figure 6 shows the effect of bed depth and bin diameter on drying capacity and specific energy consumption. The drying air temperature was 71.1° C (160° F), and the initial and final moistures were 25 and 16.5% w.b., respectively. A 9.7 kW (13 hp) axial fan was used. The effect of bed depth on capacity and SECO is similar to that described for figures 4 and 5. Bin diameter affects airflow and therefore affects the optimal bed depth. For bin diameters of 5.5 m (18 ft), 7.3 m (24 ft), and 9.1 m (30 ft), optimal performance (based on maximum capacity and near minimum SECO) is achieved at bed depths of 1.5 m (4.9 ft), 1.1 m (3.6 ft), and 0.8 m (2.6 ft), respectively. This shift in the optimum is due to a change in the depth of the drying zone for a given fan. For a larger diameter bin, the drying zone is more shallow, and the optimal depth is therefore lower than for a smaller bin. The lower drying zone depth is due to a lower airflow per grain mass (m^3/min/t) in the larger diameter bins, given the same fan and bed depth.

It would be useful to know whether one performance factor, such as the airflow rate, could explain the optimal drying bed depth for various bin diameters. Figure 7 is a plot of the airflow versus bed depth for the 9.7 kW (13 hp) axial fan for three different diameter bins. The dashed line across the plot is at an airflow of 11.1 m^3/min/t (10 cfm/bu). The points at which this line intersects the

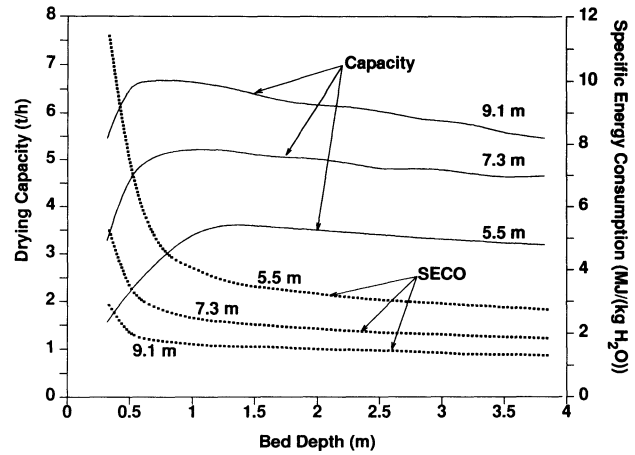

Figure 6–Drying capacity and specific energy consumption (SECO) vs. bed depth for three bin diameters (9.1 m, 7.3m, and 5.5 m). 9.7 kW axial fan. Drying air temperature 71.1°C. Drying corn from 25 to 16.5% w.b. moisture. Each curve represents 13 simulation runs.

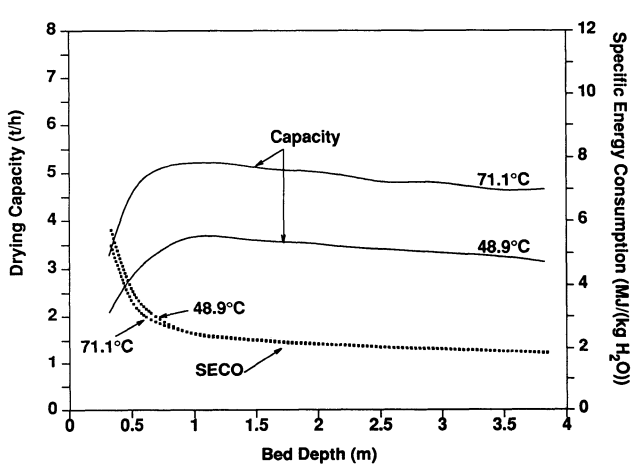

Figure 5–Drying capacity and specific energy consumption (SECO) vs. bed depth for two drying air temperatures. Bin diameter 7.3 m. 9.7 kW axial fan. Drying corn from 25 to 16.5% w.b. moisture. Each curve represents 13 simulation runs.

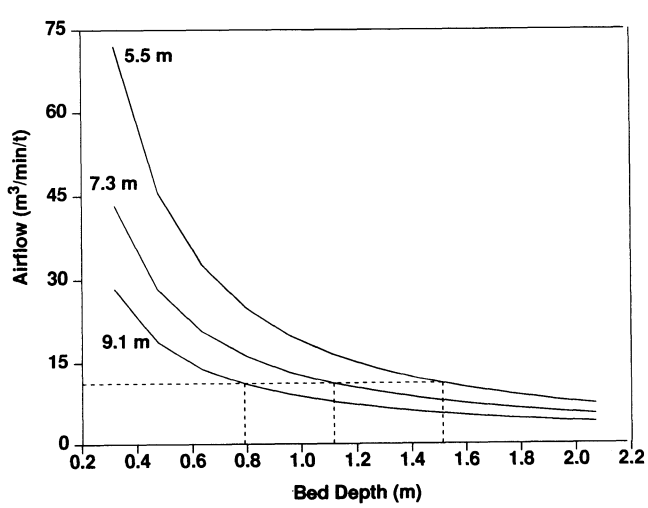

Figure 7–Airflow vs. bed depth for 9.7 kW axial fan on three different bin diameters (9.1 m, 7.3m, and 5.5m). Dashed line is at 11.1 m^3/min/t. Each curve represents 13 simulation runs.

airflow curves correspond closely to the optimal bed depths of 1.5 m, 1.1 m, and 0.8 m (4.9 ft, 3.6 ft, and 2.6 ft) previously discussed for bin diameters of 5.5 m, 7.3 m, and 9.1 m (18 ft, 24 ft, and 30 ft), respectively. This implies that, given this fan, the optimal depth can be selected by finding the depth which results in an airflow rate of approximately 11.1 m^3/min/t (10 cfm/bu) on any given bin. This implies that airflow (m^3/min/t) is the primary factor that can be used to determine optimal operating depth for a given in-bin counterflow drying system.

Lastly, figure 8 shows the effect of bed depth and fan power on drying capacity and specific energy consumption for the fan used in this study. The bin diameter was 9.1 m (30 ft). The drying air temperature was 71.1° C (160° F). The initial and final grain moistures were 25% and 16.5% w.b., respectively. The first fan examined was the 9.7-kW (13-hp) axial fan previously mentioned. The second configuration was two 9.7-kW fans in parallel for a total of 19.4-kW (26-hp) fan power, which provided between 41% and 91% greater airflow than the single fan, depending on bed depth. As shown in figure 6, the optimal depth for the 9.7 kW fan was approximately 0.8 m (2.6 ft). For the parallel fan configuration (19.4 kW), the optimal depth can be selected from figure 8 as approximately 1.3 m (4.3 ft). Thus, doubling the fan power increased the optimal bed depth by about 60%. However, the drying capacity increased by only 38%, while the SECO increased 32%. Interestingly, the optimal drying depth in both fan-bin configurations corresponds to an airflow rate near 11.1 m^3/min/t (10 cfm/bu). This further supports the claim that the airflow criterion (11.1 m^3/min/t) can be used to determine optimal bed depth for this drying system.

Conclusions

A computer model was validated with experimental data and used to successfully evaluate the performance of a new in-bin counterflow corn drying system. The recent commercial availability of the new system utilizes a leveling auger that more precisely regulates the bed depth.

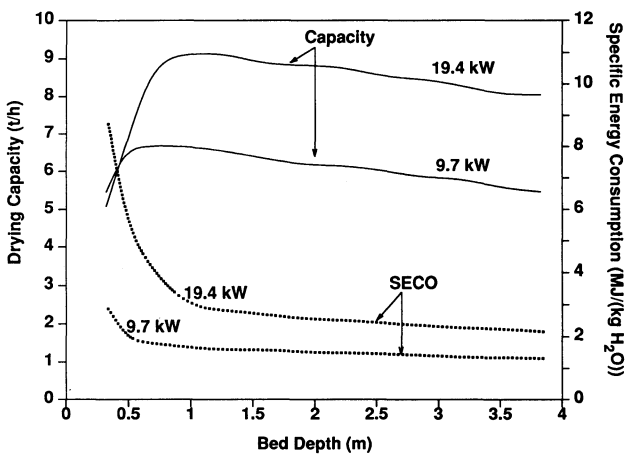

Figure 8–Drying capacity and specific energy consumption (SECO) vs. bed depth for two different fan configurations: one 9.7 kW axial fan and two 9.7 kW fans in parallel (19.4 kW total). Bin diameter 9.1 m. Drying corn from 25 to 16.5% w.b. moisture. Drying air temperature 71.1° C. Each curve represents 13 simulation runs.

Drying air temperature, initial and final moisture, bed depth, bin diameter, and fan power affected drying capacity and specific energy consumption.

Specific conclusions were:

- Drying capacity increases nearly linearly with drying air temperature. In contrast, specific energy consumption is not significantly affected by drying temperature. This was shown for two different moisture content reduction ranges (i.e., 25 to 16.5% w.b., and 22 to 17% w.b.).
- Drying capacity and specific energy consumption are significantly affected by bed depth. Therefore, for a continuous refill operation with a leveling auger, an optimal bed depth can be selected on the basis of maximum drying capacity and near minimum specific energy consumption. However, allowing the bed depth to fluctuate above the optimal bed depth may be an acceptable operating strategy to avoid the expense of a wet holding bin.
- Optimal bed depth is not significantly affected by moisture content reduction range or drying air temperature.
- Optimal operating depth varies significantly with changes in fan/bin diameter combinations. For example, drying corn from 25 to 16.5% w.b. moisture content, with 71.1° C (160° F) air and a 9.7-kW (13-hp) axial fan, yields an optimal depth of approximately 1.5 m (4.9 ft) in a 5.5-m (18-ft) diameter bin. For the same fan, in a 9.1-m (30-ft) diameter bin, the optimal depth is approximately 0.8 m (2.6 ft).
- Results indicate that the optimal bed depth can be selected on the basis of airflow for a given system. For the particular fan investigated, the optimal depth can be selected by finding the depth that corresponds nearly to an airflow rate of 11.1 m^3/min/t (10 cfm/bu).

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