DRIER PERFORMANCE AND ENERGY USE IN CORN DRYING

A.G. Meiering[1], T.B. Daynard[2], R. Brown[2], and L. Otten[1]

[1]*School of Engineering and* [2]*Department of Crop Science, University of Guelph, Guelph, Ontario N1G 2W1*

Received 28 July 1976

Meiering, A.G., T.B. Daynard, R. Brown, and **L. Otten.** 1977. Drier performance and energy use in corn drying. Can. Agric. Eng. 19: 49-54.

Batch and continuous flow simulation models were used to predict the performance and the net energy consumption of popular farm driers. The investigation showed that narrow column batch driers operating in the crossflow mode and multistage concurrent flow models preserve grain quality by keeping overheating of the grain to a minimum. Recycling of the cooling air and part of the drying air significantly reduces the energy requirements of the narrow column batch drier. Older batch and continuous flow models have the highest energy requirements and tend to overheat a larger portion of the corn being dried.

INTRODUCTION

A research program to explore the possibilities of energy-saving in corn drying was initiated in 1975, with financial support from the Ontario Ministry of Agriculture and Food, at the University of Guelph. One aim of the program was to compare the prevailing high temperature farm driers for their energy consumption and drying performance.

Simulation programs describing the various drying methods were used in this program to estimate the effects of drying parameters such as drying temperature, column thickness, number of drying stages and cooling air recycling on the development of grain temperature and moisture content, saturation of exhaust air and energy requirements. With these simulations, the drying results could be related to comparable operating conditions for all drier types, which is practically impossible by taking measurements at commercial operations during the drying season.

NOMENCLATURE

A = specific corn surface
a,b = constants
c_p = specific heat of corn
c_{p_a} = specific heat of air
D = diffusion coefficient
E = heat of evaporation
G = moisture content ratio
h = convective heat transfer coefficient
k = conductive heat transfer coefficient
n = normal to surface of seeds
P_{total} = total pressure
P_s = saturation pressure of water
r_1 = radius of clyindrical air plenum
r = radial distance in cylindrical corn column
T_a = air temperature
T_p = average corn temperature
t = time
u = time in aeration drying, column length in cross flow and concurrent flow drying
v_a = air velocity
v_{a_1} = air velocity at entrance to the corn column
v_p = velocity of corn
X_{eq} = equilibrium specific humidity
X_a = specific humidity of air
X_p = average moisture content of corn rn
X_{p_0} = average initial moisture content of corn
z = thickness of corn column or corn layer
ρ_a = density of air
$\bar{\rho}_p$ = bulk density of corn
ρ_p = apparent density of corn dry matter
σ = convective mass transfer coefficient
ϕ = relative humidity of air.

SIMULATION MODELS

A number of theoretical models for the heat and mass transfer in drying of stationary or moving beds of corn have been developed (Bakker-Arkema et al. 1974; Klapp 1963; Meiering et al. 1972; Sabbah et al. 1972; Slatyer 1967). Internal diffusion of heat and mass within the kernels has been analyzed in theory (Chen 1973; Husain et al. 1972; Meiering 1971; Slatyer 1967) but is usually neglected in the drier simulations in order to save CPU time (Bakker-Arkema et al. 1974; Baughman et al. 1971; Meiering and Hoefkes 1977). The changes in temperature, moisture content and specific humidity in a stationary grain layer or in an evenly flowing grain column in a batch, crossflow or concurrent flow drier can then be defined (Bakker-Arkema et al. 1974; Bakker-Arkema et al. 1973; Klapp 1963; Meiering et al. 1971, 1972).

$$\frac{\delta T_a}{\delta z} = \frac{h\,A}{v_a\,\rho_p\,c_{p_a}}\,(T_a - T_p) \quad \ldots\ldots\ldots\ldots \text{(1a)}$$

$$\frac{\delta T_p}{\delta u} = \frac{h\,A}{v_p\,\bar{\rho}_p\,c_p}\,(T_a - T_p) - \frac{E\sigma A}{v_p\,\bar{\rho}_p\,c_p}\,(X_{eq} - X_a) \quad \ldots\ldots\ldots\ldots \text{(1b)}$$

$$\frac{\delta X_a}{\delta z} = \frac{\sigma A}{v_a\,\rho_a}(X_{eq} - X_a) \quad \ldots\ldots\ldots\ldots \text{(1c)}$$

$$\frac{\delta X_p}{\delta u} = \frac{\sigma A}{v_p\,\rho_p}(X_{eq} - X_a) \quad \ldots\ldots\ldots\ldots \text{(1d)}$$

with (Gustafson and Hall 1974; Kazarian and Hall 1963)

$$\sigma = \frac{h(X_{eq} + 0.622)}{0.622\,c_{p_a}} \quad \ldots\ldots\ldots\ldots \text{(2)}$$

$$X_{eq} = 0.622\,\frac{\phi P_s}{P_{\text{total}} - \phi P_s} \quad \ldots\ldots\ldots\ldots \text{(3)}$$

$$\phi = exp(\,(-AT_p)\,exp(-BX_p)\,) \quad \ldots\ldots\ldots\ldots \text{(4)}$$

$$D = D(X_p, T_p) \quad \ldots\ldots\ldots\ldots \text{(5)}$$

$$K = K(X_p, T_p) \quad \ldots\ldots\ldots\ldots \text{(6)}$$

The term v_p representing the corn velocity is omitted from system 1 when the drying process of a stationary grain layer is simulated. The variable u represents the drying time in batch drying of a stationary grain bed and the length of the grain column in crossflow and concurrent flow driers. The air velocity in equations 1a and 1c assumes the value $v_a = v_{a_1}\,r_1/r$ for driers having a central cylindrical air plenum and a cylindrical grain column surrounding it (Klapp 1963). System 1 does not account for kernel deformation and describes steady state processes only.

The concept of using an average kernel temperature does not introduce significant differences between simulated and measured grain temperatures (Meiering 1971). Differences do occur, however, between predicted and measured values of moisture content due to the comparatively larger Biot-numbers of mass transfer. The relative humidity cannot be calculated as a function of average moisture content according to equation 4 if high drying temperatures are used, which create strong moisture gradients within the kernels. The effect of the internal moisture gradient on the equilibrium relative humidity at the kernel surface can be approximated by forming the moisture content ratio $G = X_p/X_{p_0}$ and introducing it into equation 4, as discussed by Mieiring (1977).

$$\phi \text{ surface} = a + \phi G^b \quad \ldots\ldots\ldots\ldots \text{(7)}$$

Equation 7 was used with $a = 0$ and $b = 3.0$ in

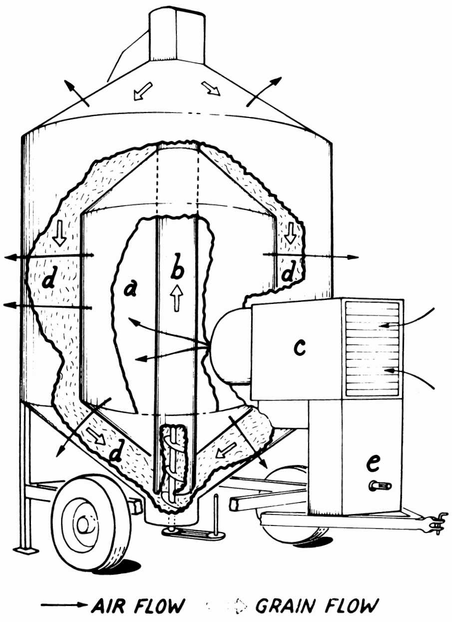

Figure 1. Crossflow batch drier with agitated rotating corn charge and circular drying column. Drier capacity: 5 - 9 tons/h. a. hot air plenum, b. central auger, c. fan and burner assembly, d. corn column, d. p.t.o. connection.

TABLE I. PHYSICAL PROPERTIES OF CORN

Property	Symbol	Value
Spec. grain surface area	A	844 m²/m³
Bulk density of corn	$\bar{\rho}_p$	684 kg/m³
Heat transfer coefficient	h	84 kJ/m²h C
Avg. heat of evaporation	E	2,500 kJ/kg
Spec. heat of grain	c_p	2.13 kJ/kg C
Spec. heat of air	c_{p_a}	1.02 kJ/kg C

high temperature crossflow drying and equation 4 for low temperature and concurrent flow drying.

The simulation models were tested with data obtained from a pilot scale drier and from commercial models. Simulated and measured results were in good agreement (Meiering and Hoefkes 1977). The vapor pressure was calculated with the Clausius-Clapeyron equation and the thermal conductivity as a function of moisture content according to Kazarian and Hall (1963). Other properties were used as given in Table I. An implicit finite difference method was employed to solve system 1.

The performance of corn driers prevailing on Ontario farms was simulated on the basis of system 1. Energy data were calculated as net values for heating of the drying air or for heating and cooling of the grain. Efficiencies of burner equipment were not considered.

RESULTS AND DISCUSSION

Batch Drying

In batch drying, a drier is charged with a certain amount of wet grain, which stays in the drier until the desired final moisture content is reached. No grain leaves or enters the charge during the drying process. Depending on drier design, the grain is agitated in the drier or kept stationary during drying. A popular model of a batch drier is shown in Fig. 1. After this drier is charged with wet grain, the central auger rotates the charge through the circular drying columns formed between the perforated outer wall and inner plenum. The drying process follows the crossflow pattern. The drier does not have a cooling section and can remove between 5 and 8% of moisture per hour from 5 - 9 tons of grain, depending on drier size and operating conditions. The grain can be cooled at the end of drying by rotating it without heating.

Based on the input data given in Table I, the drying pattern in Fig. 2 was established by simulation. In the first passing of the grain through the drier, only the inner half of the grain column is dried. At a depth of 22.5 cm, the moisture removal has just begun. Some condensation occurs in the other half because the saturated air is cooled down by the cold grain and, therefore, deposits some water. The grain temperature near the air plenum rises to the drying temperature of 80 C along two thirds of its total way. Only slight overdrying occurs near the plenum. A similar pattern of temperature development and more severe overdrying would occur if high drying temperatures were used. The maximum recommended drying temperature of 80 C as recommended by the manufacturer should, therefore, not be exceeded.

When the dried grain reaches the central auger, the wet and overdried portions are mixed thoroughly in the elevating process to an average moisture content of 22.7% w.b. In the second pass, a drying pattern similar to the first one is established (Fig. 2). The only difference is that the drying zone penetrates slightly further and no condensation occurs in the undried section, which was heated to the equilibrium drying temperature of approximately 26 C in the first pass. Portions of the grain near the plenum are overdried. The grain is dried from 22.7% w.b. to 16.3% w.b. in the second pass (Table II).

In the final pass, the grain is aerated with unheated air and cools down to the environmental temperature of 10 C. The stored heat in the grain allows a drying effect of

TABLE II. DRYING CAPACITY AND ENERGY REQUIREMENTS OF DIFFERENT TYPES OF FARM DRIERS.

Drier type	Length of grain column		Column depth	Temperatures		Air flow		Grain flow		Max. grain temp.	Grain moisture content		Energy cool'g air exh.	Req'd cool'g air recyc'd	Energy saved by recycling	Avg. energy for multiple pass
	Drying (m)	cooling (m)	(m)	Drying (C)	Cooling (C)	Q (m³/m²h)	P (mm)	t/h	m/h	(C)	In. (% w.b.)	Fin. (% w.b.)	(kJ/kg water)	(kJ/kg water)	(%)	(kJ/kg)
Rotating																
Batch	4.0	—	0.45	80	—	1,100	38	7.5	3.05	80	27.5	22.7	5,243	—	—	
Crossflow	4.0	—	0.45	80	—	1,100	38	7.5	3.05	80	22.8	16.	4,265	—	—	4,000
+	4.0	—	0.45	—	10	1,100	38	7.5	3.05	10	16.1	14.2	0	—	—	
Drieration	—	—	2.00	10	—	500	49	—	—	10	16.1	14.4	0	—	—	4,138
Rotating																
Batch	2.5	1.0	0.1	80	10	1,500	14	3.5	12.4	69	27.5	20.8	4,282	3,249	24	
Crossflow	2.5	1.0	0.1	80	10	1,500	14	3.5	12.4	76	20.8	14.1	4,656	3,560	24	3,398
Crossflow	2.5	1.0	0.1	80	10	1,500	14	1.2	4.2	80	27.5	13.6	6,588	5,796	12	—
Single pass	2.1	-.9	0.3	80	10	2,000	67	2.8	2.2	80	27.5	14.8	5,063	(4,216)	(17)†	—
Concurrent	Single stage		0.5	150	10	2,000	112	0.4	0.6	41	27.5	16.8	3,844	(3,466)	(10)	—
flow	Triple Stage		0.5	150	—	4,000	364	2.0	2.9	35	27.5	24.3	4,642	—		3,792
			0.5	150	—	4,000	364	2.0	2.9	41	24.3	19.4	3,456	—	9%	(3,453)
			0.5	150	10	4,000	364	2.0	2.9	45	19.4	14.0	3,491	(2,555)		

†Numbers in parentheses refer to energy requirements and savings that could be achieved if the cooling air was recycled.

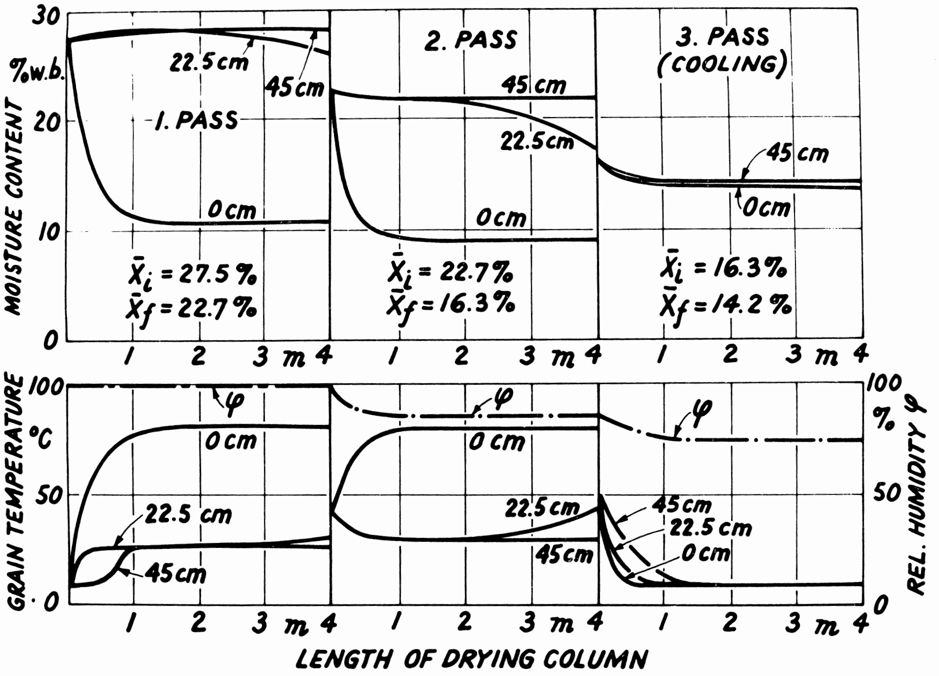

Figure 2. Performance of rotating batch crossflow drier. Drying column length: 4.0 m; drying column depth: 0.45 m; grain flow: 3.05 m/h; air flow: 1,100 m^3/m^2h; drying temperature: 80°C.

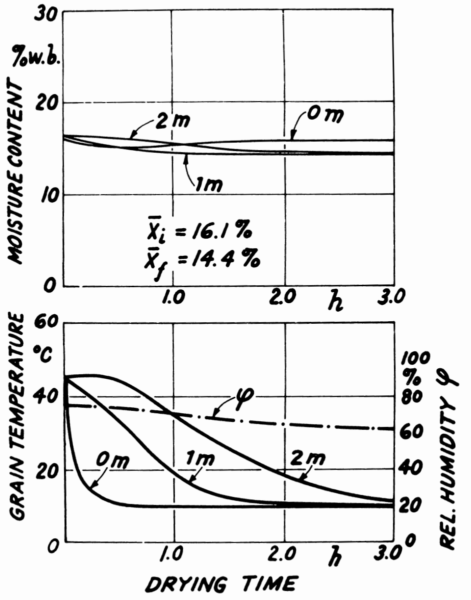

Figure 4. Drieration results of corn aerated in bin with floor ducting. Grain depth: 2.0 m; air flow: 500 m^3/m^2h.

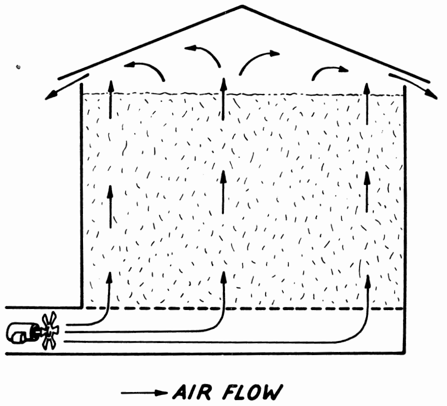

Figure 3. Drieration in a bin with floor ducting.

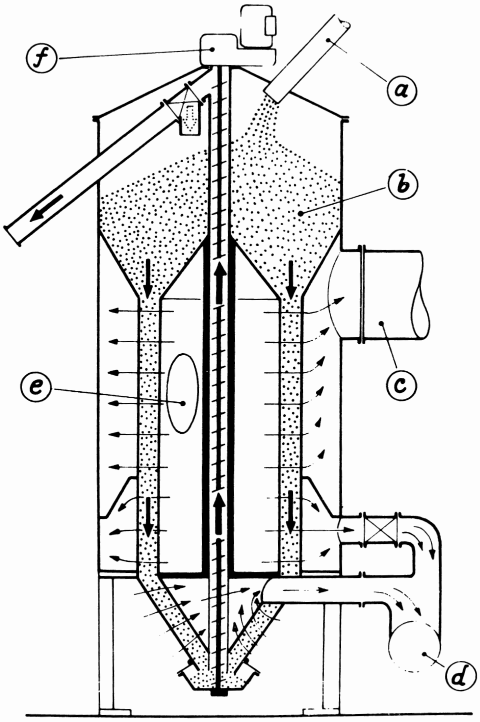

Figure 5. Crossflow batch drier with rotating corn charge and circular narrow drying column. Drier capacity: 3.5 to 10 tons/h, depending on optional column length. a. feed auger, b. corn hopper, c. exhaust, d. recycling duct, e. hot air plenum, f. central auger.

2.1% w.b. in the cooling pass.

The rotating batch crossflow model dried 7.5 t of corn from an initial moisture content of 27.5% w.b. to a final moisture content of 14.2% w.b. in a total time of approximately 3 h, amounting to a capacity of 2.5 t/h. The exhaust air was completely saturated in the first pass, so that no drying energy was lost. Heating of the corn to the equilibrium drying temperature and partial overheating, however, caused a high energy requirement of 5,243 kJ/kg water evaporated (see Table II). In the second pass, there is only little heating energy required for the corn, but most of the exhaust air is only saturated to approximately 80%, resulting in a moderated energy requirement of 4,265 kJ/kg water evaporated. In the final cooling pass, the energy balance is greatly improved, since no heating is required for the air, and the heat stored in the grain in the first pass is now used for evaporation. The energy balance of all stages therefore improves to an overall 4,000 kJ/kg water evaporated. A similar balance can be obtained by substituting the final cooling pass through a drieration process as shown in Figs. 3 and 4. Drieration would help to significantly reduce quality damages of cooling corn from 80 C down to 10 C in a rapid cooling pass. Some of the heat stored in the corn would likely be lost, however, during tempering time. The initial temperature of the drieration simulation was, therefore, assumed to be 45 C only, resulting in a slightly higher final moisture content of 14.4% w.b. (Table II).

Considerable amounts of energy can be saved if the exhaust air from the cooling sections of crossflow driers is recycled to the drying process. The specific humidity of this air is sufficiently low as to not impair the drying capacity of the heated air. Slightly higher moisture concentrations of the drying air may even have beneficial effects by limiting overdrying to some small extent.

A German drier model with recycling of the exhaust air from the cooling section is shown in Fig. 5. This model has a very narrow column depth and high grain speed to limit the extent of overdrying. Its drying pattern was also established by simulation and the results are shown in Fig. 6. Overdrying of the corn in the narrow column model is eliminated in the first pass and the amount of condensation is significantly reduced (Fig. 6). Also, the corn temperature does not reach the drying air temperature, which is safer with respect to quality damages. In addition, the corn is only briefly exposed to its maximum temperature of approximately 70 C in the first pass. The drying zone penetrates the entire corn column so that unsaturated drying air is exhausted from the lower part of the drying section. The grain is cooled from approximately 70 C to 10 C in the cooling section.

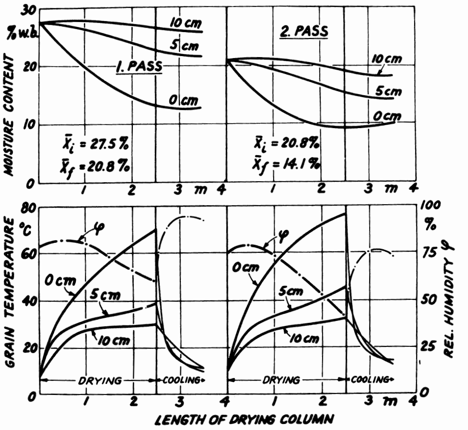

Figure 6. Performance of rotating batch cross flow drier with recycling of cooling air. Drying column length: 2.5 m; cooling column length: 1.0 m; column depth: 0.1 m; grain flow: 12.4 m/h; air flow: 1,500 m³/m²h; drying temperature: 80° C.

In the second pass, some overdrying to approximately 9.2% w.b. occurs but penetrates only to a depth of approximately 1 cm into the drying column. The corn temperature near the hot air plenum rises to 76 C at the point of exit from the drying column but stays well below this temperature for almost the entire column length.

The narrow column batch crossflow model dried 3.5 t of corn from an initial moisture content of 27.5% w.b. to a final moisture content of 14.1% w.b. in a total time of approximately 2 h, amounting to a capacity of 1.25 t/h. This capacity can be increased through optional extension of the column length. The exhaust air is only partially saturated and some drying energy is lost, therefore, in both drying passes. Recycling of the cooling air nevertheless assures the low energy requirements of 3,249 kJ/kg water in the first pass and 3,560 kJ/kg water in the second pass (Table II). This energy balance was still improved through recycling of some part of the unsaturated exhaust air from the drying section. Sufficient details about this recycling procedure, which also involves some electronic control equipment to assure a stable profile of the relative humidity in the exhaust air along the drying column, were not known and therefore not included in the simulation.

Continuous Flow Drying

A popular dual column continuous flow drier operating in the crossflow mode is shown in Fig. 7. The corn is dried in one pass. Heating and cooling air are delivered by the same fan. The cooling air is not recycled and the total drying capacity amounts to 2.8 t/h. This unit is mobile and can be operated with the p.t.o. of the tractor.

Figure 8 shows that condensation and minor overdrying occur in this model up to a depth of 5 cm of the corn column. Also, the corn near the hot air plenum is heated to the drying air temperature of 80 C along two thirds of the drying section. This grain temperature development precludes higher drying temperatures, if quality losses are to be avoided.

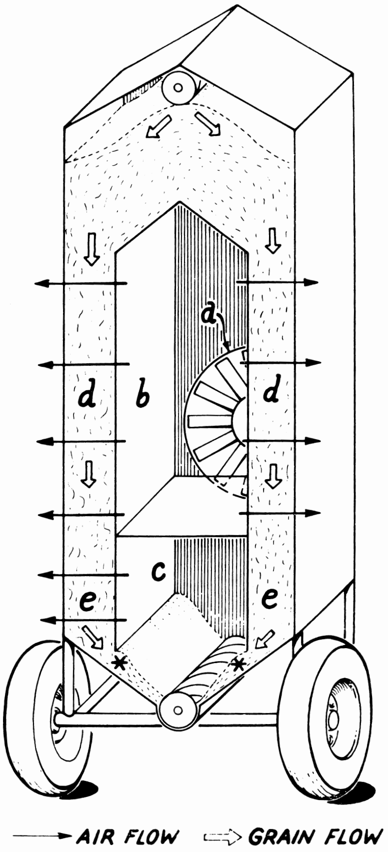

Figure 7. Dual column continuous cross flow drier. Drier capacity 1.4 tons/h per column. a. radial fan, b. hot air plenum, c. cooling air plenum, d. drying column, e. cooling column.

The dual column continuous flow model dried a total of 2.8 t of corn from an initial moisture content of 27.5% w.b. to a final moisture content of 14.8% w.b. in 1 h. The exhaust air from the drying section is saturated along its upper half and decreases to a minimum of 60% in its lower half. Minor losses of drying energy occur, therefore, in this region. The drying process requires 5,063 kJ/kg of water evaporated. This rather high amount can be reduced to an acceptable 4,216 kJ/kg if the cooling air is recycled, amounting to an energy saving of 17% (Table II). Installation of a ducting system in these driers can be achieved with relatively little effort.

Another popular drier is the concurrent continuous flow model shown in Fig. 9. Corn and drying air move in the same direction and the cooling air in the opposite direction of the corn. Very high drying temperatures can be used in these driers, since the air with the highest temperature meets the corn with highest moisture content. This enhances efficient evaporation and an according rapid temperature reduction of the drying air immediately upon entry into the corn column. The drying capacity is approximately 0.4 t/h/m² of column cross section and the corn is dried in a single pass.

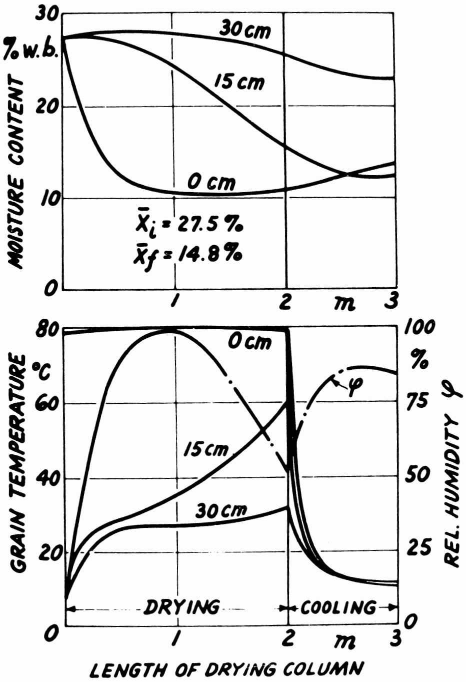

Figure 8. Performance of continuous cross flow drier. Drying column length: 2.1 m; cooling column length: 0.9 m; column depth: 0.3 m; grain flow: 2.2 m/h; air flow: 2,000 m³/m²h; drying temperature: 80° C.

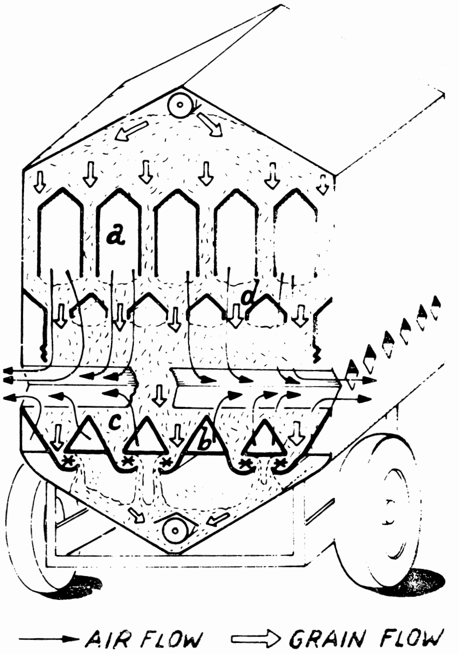

Figure 9. Single stage concurrent flow drier. Drier capacity: 0.4 ton/h per m² cross section. a. hot air plenum, b. cooling air plenum, c. cooling column, d. drying column.

Figure 10 shows that the moisture content of the corn is reduced uniformly across

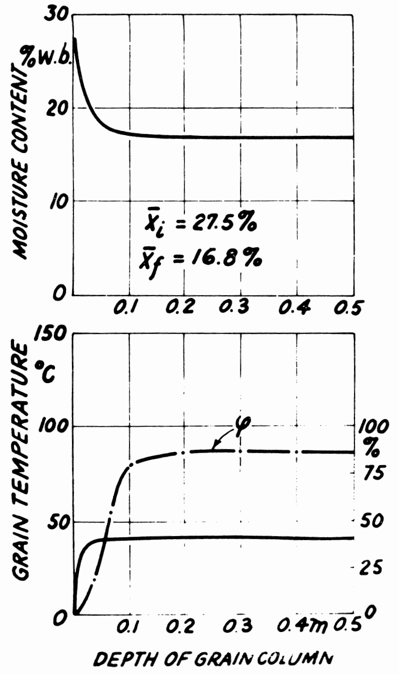

Figure 10. Performance of concurrent flow drier. Drying column length: 0.5 m; grain flow: 0.4 m/h; air flow: 2,000 m³/m²h; drying temperature: 150°C.

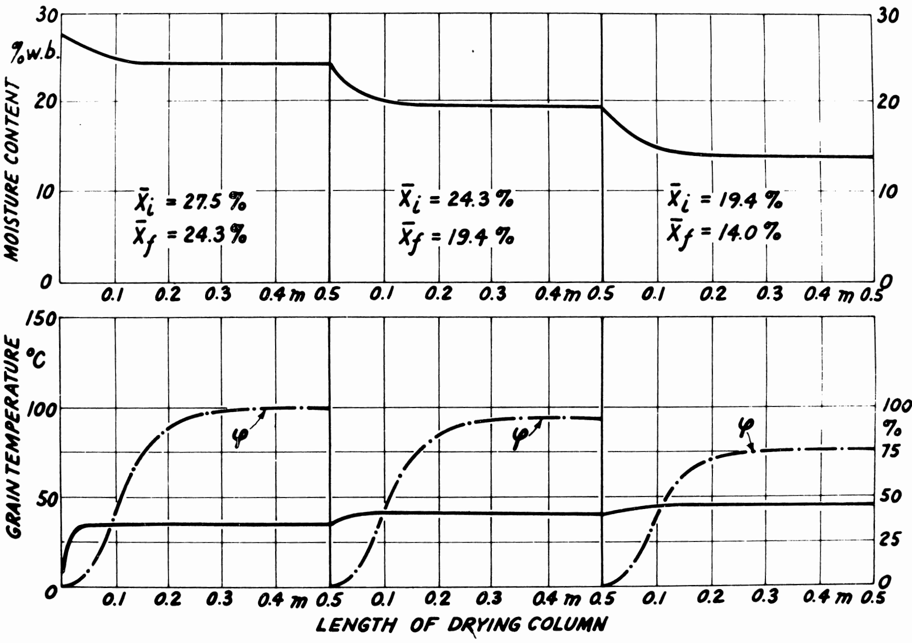

Figure 12. Performance of triple stage concurrent flow drier. Drying column depth: 0.5 m; grain flow: 0.6 ton/h; air flow: 1,500 m³/m²h; drying temperature: 150°C.

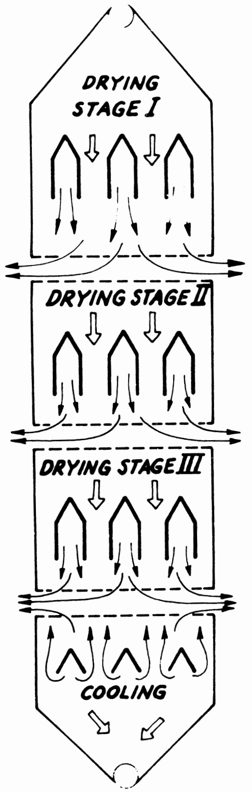

Figure 11. Triple stage concurrent flow drier. Drier capacity: 0.6 ton/h per m² cross section.

the corn column and that no overdrying or condensation can occur in steady state concurrent flow drying. Due to the intensive evaporation near the entrance section, the grain temperature remains at a safe 41 C, even at a drying temperature of 150 C (Table II). The exhaust air from the drying action reaches a relative humidity of 87% if the corn is dried to 16.8% w.b. Approximately 2.0% moisture is removed in the counterflow cooling section. The energy requirement amounts to 3,844 kJ/kg water evaporated. If the cooling air in the single-stage drier shown in Fig. 9 is recycled, only 3,466 kJ/kg would be required, representing an energy saving of 10%.

A tempering effect can be achieved in concurrent flow drying, if the corn is dried in consecutive stages, as shown in Fig. 11. A new design by Westelaken Agricultural Engineering Co., St. Mary's, Ontario, has three consecutive stages. The corn has the opportunity to reduce the interior moisture gradients during the time it travels between the stages. It passes only one cooling section just before leaving the drier.

Figure 12 shows a drying example of a triple-stage concurrent flow drier. The moisture content is reduced from an initial 27.5% w.b. to 24.3% w.b. in the first stage, from 26.3% w.b. to 19.4% w.b. in the second stage and from 19.4% to 14.0% w.b. in the third stage. These moderate reductions, together with the tempering effect while travelling from stage to stage, greatly enhance preservation of corn quality. The corn temperature never rises higher than a safe 45 C. The exhaust air reaches over 90% saturation in the first two stages. A relative humidity of 75% is reached in the third stage, which causes minor energy losses. Energy requirements are 4,642 kJ/kg, 3,456 kJ/kg and 3,491 kJ/kg, respectively, amounting to an overall requirement of 3,792 kJ/kg (Table II). Recycling of the cooling air would save 9% of the total energy and reduce the requirement to 3,453 kJ/kg.

CONCLUSIONS

Concurrent flow drying appears to be, in principle, the optimal form of corn drying. Special efforts must be taken, however, to assure an absolutely reliable and even corn flow. Corn passages must be sufficiently wide to prevent bridging or blocking by foreign materials, since temperature damage would be more severe in case of interruptions. Narrow column crossflow drying with recycling of the cooling air and portions of the drying air is a close second choice. Due to lower drying temperatures, it offers greater safety in case of interrupted or irregular corn flow. The recycled air should not pass the burner to avoid ignition of its eventual red dog content. Heating is to be limited to the fresh air intake duct. A settling chamber for particulate can be included in the recycling passage.

ACKNOWLEDGMENTS

The research described in this paper was sponsored by the Ontario Ministry of Agriculture and Food and the Ontario Ministry of the Environment in the form of Research Contracts with the University of Guelph.

BAKKER-ARKEMA, F.W., L.E. LEREW, S.F. DE BOER, and M.G. ROTH. 1974. Grain drier simulation. Res. Rep. 224, Mich. State Univ. Exp. Sta., Jan.

BAKKER-ARKEMA, F.W., D.M. FARMER,

and L.E. LEREW. 1973. Optimum grain drier design through simulation. Ann. Tech. Agric. 22(3), S. 275.

BAUGHMAN, G.R., M.Y. HAMDY, and H.J. BARRE. 1971. Analog computer simulation of deep-bed drying of grain. Trans. Amer. Soc. Agric. Eng. no. 6, S. 1058.

CHEN, C.S. 1973. Simulataneous heat and mass transfer in convective drying of biological materials. Ann. Tech. Agric. 22(3), S. 305.

GUSTAFSON, B.J. and G.E. HALL. 1974. Equilibrium moisture content of shelled corn from 50 to 150° F. Trans. Amer. Soc. Agric. Eng. Vol. 15 no. 1, S. 120.

HUSAIN, A., C.S. CHEN, J.T. CLAYTON, and L.F. WHITNEY. 1972. Mathematical simulation of mass and heat transfer in high moisture foods. Trans. Amer. Soc. Agric. Eng. no. 4, S. 732.

KAZARIAN, E.A. and C.W. HALL. 1963. The thermal properties of grain. Amer. Soc. Agric. Eng. Pap. no. 63-825, Chicago, Dec.

KLAPP, E. 1963. Mathematische Behandlung gekoppelter Wärme- und Stoffaustauschvorgange in durchstromten Schüttgutern. (Mathematical treatment of simultaneous heat and mass transfer in aerated beds of particles). Ingenieur-Archiv, Bd 32 H. 5, S. 360.

MEIERING, A.G., W.H. CLIFFORD, and F.W. BAKKER-ARKEMA. 1972. Drying of a bed of composted waste. Trans. Amer. Soc. Agric. Eng. Vol. 15 no. 1, S. 116.

MEIERING, A.G. 1971. Der gekoppelte Wärme- und Stoffaustausch bei der Verarbeitung von Nahrungsmitteln unter besonderer Berüchsichtigung der Trocknung von Körnerfrüchten. (Simultaneous heat and mass transfer in processing of foods with special consideration of grain drying). VDI-Fortschritt-Bericht, Reihe 14 Nr. 14, 98 pp.

MEIERING, A.G. and H.J. HOEFKES. 1977. Die Bestimmung des Trocknungsverlaufs und des Energiebedarfs der Kornertrocknung mit Hilfe der Computersimulation. (The determination of performance characteristics and energy use of grain driers through computer simulation). Grundl. Landtechnik, Bd. 26 no. 1, pp. 1-8.

SABBAH, M.A., G.H. FOSTER, C.H. HAUGH, and R.M. PEART. 1972. Effect of tempering after drying on cooling shelled corn. Trans. Amer. Soc. Agric. Eng. Vol. 15 no. 4, S. 763.

SLATYER, R.O. 1967. Plant-water relationships. Academic Press, London, New York, N.Y.