CIGR - E Journal

Capacity Estimation of High-Temperature Grain Dryers
— A Simplified Calculation Method —

By
Qiang Liu and F. W. Bakker-Arkema
Department of Agricultural Engineering
Michigan State University
East Lansing, MI 48824, USA

Abstract

A simplified procedure for the capacity calculation of batch-in-bin and crossflow grain dryers has been developed by making a number of simplifying assumptions in the heat and mass transfer equations. The calculations require only a hand calculator and a psychrometric chart. Dryer-capacity data computed with the new procedure are within ± 10% of those obtained experimentally or those calculated by computer simulation. The method provides a simple and rapid procedure to predict the effect of the drying temperature and the airflow rate on dryer capacity.

1. Introduction

To determine the capacity of high-temperature grain-drying installations, e.g. batch-in-bin and crossflow dryers, experimental tests are conducted or computer simulations are run. Drying experiments are time-consuming and costly, computer simulations require sophisticated models and computation familiarity.

The objective of this study was to develop a *simplified* procedure for calculating dryer capacity. The procedure should be accurate to ± 10%, should only need a calculator and some graphs, and should be simple to implement.

The development of a simplified capacity-calculation procedure of a complicated process often requires that some simplifying assumptions are made which scientifically cannot always be justified but which are *pragmatically warranted* because they lead to *useful results.* As will be shown, this was the case in the development of the simplified procedure for calculating the capacity of high-temperature grain dryers.

2. Literature Review

Establishing the capacity of a grain-drying system under different ambient conditions, at different airflows and temperatures, and for different grain types, is time-consuming and costly. Therefore, dryer manufacturers usually rely on simulation models (Brooker et al., 1992).

Grain-drying models are based on the laws of heat and mass transfer and lead to rather complicated systems of equations. The models can be solved only with the aid of digital computers. Two dryer models are considered in this paper, batch-in-bin and crossflow. Both dryer types are modeled by similar systems of four differential equations (Laws and Perry, 1993). Some authors, e.g. Hukill (1954), Morey et al. (1979), simplified the basic models by making simplifying assumptions;

however, these models still require computer solutions, and thus are not suitable for quick hand-calculation.

The authors have not found any papers in the literature on the hand-calculation of the throughput of batch-in-bin and crossflow grain-drying systems.

3. Procedure Background

Consider a stationary grain-layer of thickness H, length L, and width D to be dried and shown in Fig. 1. The flowrate of drying air is G_a (kg m^{-2}h^{-1}), the inlet-air conditions are T_{in} (^{o}C) and W_{in} (kg kg^{-1}). The initial grain moisture content and temperature are M_i (dec., d.b.) and q_i (^{o}C), respectively. The question is what are the average final grain moisture content M_f and temperature q_f after as a function of time t (h).

To facilitate *hand-calculation* of the throughput of a drying system, a series of simplifying assumptions are required in the fundamental solution procedure. [*Note:* it should be remembered that the basic differential-equation drying model is also subject to a series of assumptions (Brooker et al., 1992).] However, if it is shown that the simplifying assumptions hardly affect the result, i.e. the calculation of dryer capacity, the additional assumptions are *justified for practical reasons.*

In the simplified dryer-capacity model, the grain layer is divided into a number of sub-layers of *dissimilar* thickness (see Fig. 1). It is assumed that within the sub-layers the grain and air temperatures are equal; the moisture content and (air/grain) temperature are uniform; and the thin-layer drying equation expresses the drying rate of the grain in a sub-layer. Thus (Brooker et al., 1992):

$$\frac{M_f - M_e}{M_i - M_e} = \exp(-k\Delta\tau) \tag{1}$$

The value of the drying constant k for maize is (Pabis and Henderson, 1961):

$$k = 1941 \exp\{-5032 / [1.8(T_i + 273)]\} \quad (2)$$

The equilibrium moisture content of grains can be expressed by (Brooker et al., 1992):

$$M_e = 0.01[\frac{\ln(1-f)}{-A(T+B)}]^{\frac{1}{C}} \quad (3)$$

where for maize A = 8.6541 x 10^5, B = 1.8634 and C = 49.81, T= air temperature, ^oC and f =relative humidity, decimal.

Making a moisture balance on a sub-layer in the grain (see Fig. 1) results in:

$$(M_i - M_f)(r_g)(\Delta H)(LD) = \Delta W(G_a)(LD)(\Delta t) \quad (4)$$

or

$$\Delta H = \frac{\Delta W}{M_i - M_f} \frac{G_a \Delta \tau}{\rho_g} \quad (5)$$

For maize the dry matter bulk density (r_g) is equal to 613 kg m^{-3} (ASAE, 1998).

The drying of grains in batch-in-bin and crossflow dryers can be illustrated on a psychrometric chart (see Fig. 2). The point P_o represents the ambient air condition before the heater, and P_1 is the condition of the air after heating.

If the energy loss of the air in the grain layer is negligible, the drying process will follow an iso-enthalpy line on the psychrometric chart (P_1-P_{out} on Fig. 2). The slope of the real process line (P_1-P'_{out}) is slightly smaller than the iso-enthalpy line because a portion of the energy of the drying air is needed for the temperature rise of the grain.

The slope of the real drying-process line can be estimated if the average outlet relative humidity f_{out} and the change of the enthalpy Δh are known. To ascertain the value of Δh, an overall heat balance and moisture balance of the air and grain in the grain dryer are made:

$$r_g(LDH)[(c_g + c_w M_f)q_f - (c_g + c_w M_i)q_i] = -(G_a t)\Delta h(LD) \tag{6}$$

$$r_g(LDH)(M_i - M_f) = (G_a t)(W_{out} - W_{in})(LD) \tag{7}$$

Solving equations (7) and (8) yields the change of the enthalpy of the drying air:

$$\Delta h = -\frac{\left[(c_g + c_w M_f)\theta_f - (c_g + c_w M_i)\theta_i\right](W_{out} - W_{in})}{M_f - M_i} \tag{8}$$

The values of the final grain temperature q_f and of the average relative humidity f_{out} can be established by an iteration method, but for practical purposes they can be estimated based on dryer specifications. [*Note:* the outlet grain temperature before cooling in commercial high-temperature dryers is generally in the range of 45-60^{o}C, and the average exhaust relative humidity of the air is in the range of 60-90%. The values can be assumed to be q_f = 50^{o}C and f_{out} = 60%, respectively.]

4. Calculation Procedure

4.1 Batch-in-Bin Dryers

The procedure for hand-calculating the throughput, or the exit moisture content, for a batch-in-bin grain dryer consists of superimposing the curves of the drying constant k (see equation (2)) and of the equilibrium moisture content M_e (see equation (3)) of the particular grain on a psychrometric chart, followed by implementing a series of eight procedural steps (see Figs. 2 and 3):

(1) Locate point P_o of the ambient air condition T_o and W_o (or f_o).

(2) Find point P_1 of the heated-air condition T_1 and W_1.

(3) Draw the iso-enthalpy line from P_1 to the f_{out} curve, assuming f_{out} = 60%.

(4) Calculate Δh from equation (8), find P'_{out} and draw the drying-process line P_1 - P'_{out}.

(5) Select a value for ΔW, i.e. the increment of the humidity ratio of the air through each sub-layer.

(6) Mark the points P_2, P_3 . . . on the drying-process line (P_1 - P'_{out}), i.e. the air conditions at the boundaries of each sub-layer, and read the drying constant and equilibrium moisture content (Fig. 3) corresponding to each point.

(7) Calculate the moisture content (M_{fi})of the grain in each sub-layer after Δt (h) of drying using equation (1). Calculate the thickness (ΔH) of each sub-layer of grain (see Fig. 1) using equation (5) for the selected (and constant) value of ΔW. *Note:* If the accumulated thickness of the sub-layers ($\sum H_i$) is larger than the actual thickness of the grain bed (*H*), the thickness of the last sub-layer (*n*) is corrected by the following equation:

$$\Delta H_n = H - \sum_{j=1}^{n-1} \Delta H_j \tag{9}$$

(8) Average the moisture contents of the sub-layers to obtain the *average* final moisture content of the bed:

$$M_f = \frac{\sum_{j=1}^{n} \Delta H_j M_{fj}}{H} \tag{10}$$

4.2 Crossflow Dryers

The procedure for hand-calculating the capacity of a crossflow dryer is an extension of the method for calculating the average moisture content in a stationary bed of grain, as illustrated in section 4.1. Namely,

(1) Choose a time increment Δt .

(2) Follow steps 1-8 in section 4.1.

(3) Repeat step 2 above for the next time period. [To simplify the calculation, assume that the moisture content in the grain column is uniform, and is equal to the average moisture content after the previous time period.]

(4) Repeat step 3 above until the average final moisture content has reached the desired moisture content.

(5) Find the capacity of the grain dryer Q_g from:

$$Q_g = \frac{r_g (LDH}{t}(1+M_f) \tag{11}$$

5. Validation

The simplified dryer-capacity calculation procedure was first validated by comparing the calculated moisture contents with the experimental batch-in-bin drying data of Gustafson and Morey (1981). The results are shown in Table 1. The error in the calculated final moisture content ranges from +0.5% to -2.2% (w.b.). Considering that the moisture removal is 15-20% (w.b.), the calculation error is small.

A second validation consisted of a comparison of the simplified procedure with data of a previously-validated differential-equation type crossflow dryer model (see Table 2). The difference in the capacities obtained by hand-calculation and computer simulation is less than 10%.

The results illustrated in Tables 1 and 2 convinced the authors of the *practical* use of the simplified calculation procedure.

The effect of the values of Δt and ΔW on the hand-calculated exit moisture content of maize dried in a crossflow dryer is illustrated in Table 3. As the data show, the effect is small, of Δt as well as of ΔW. Thus, the choices of Δt = 0.25 h and ΔW = 0.004 kg kg^{-1} are recommended.

6. Examples

6.1 Batch-in-Bin Dryers

A batch-in-bin drying system requires the use of a relatively thin layer of grain, and a moderately high flowrate of air. The drying-air temperature should not exceed 50-60 ^{o}C in order to minimize the moisture gradient in the bin (Brooker et al., 1992). It is considered to be a *stationary* system because the grain does not move during the drying operation.

The operating conditions of the batch-in-bin drying of maize used in this example are given in Table 4. The question is what the *average* moisture content of the maize is after 15 minutes (0.25h) of drying. [Note that in this example the drying-air temperature (90 ^{o}C) is excessively high. This temperature was selected because the results are used in Example 2 in section 6.2 in which the capacity of a crossflow maize dryer operating at 90 ^{o}C is calculated.]

Table 5 shows the results, obtained with the simplified calculation procedure, of the moisture content of maize dried in the batch-in-bin dryer. After 15 minutes, the average moisture content of the maize has decreased from 0.25 to 0.277 (d.b.). The increase in the thickness of the sub-layer (ΔH), and the decrease of the drying constant (k) in subsequent layers, are evident. Also shown is the moisture gradient in the bin after 15 minutes of drying, i.e. 0.20 near the air inlet, and (still) 0.25 (d.b.) near the air outlet.

6.2 Crossflow Dryers

In a crossflow grain dryer, the air flows perpendicular to the flow direction of the grain. The grain layer is relatively thin, the airflow rate is high, and the drying-air temperature is moderate, i.e. 90-120 ^oC (Brooker et al., 1992). Conceptually, the batch-in-bin dryer and the crossflow dryer have much in common; the crossflow dryer can be simulated as a series of batch-in-bin dryers in which the grain is dried for successively longer periods of time. Therefore, the capacity calculations for a batch-in-bin dryer form the basis for the calculation of the capacity of a crossflow dryer, if both operate under similar conditions.

The operating conditions of the crossflow dryer are tabulated in Table 4; they are the same as for Example 1 in which the average moisture content of maize dried in a batch-in-bin system was found. In Example 2, the capacity of the crossflow dryer in drying maize from 0.25 to 0.17 (d.b.) will be calculated.

Table 6 shows the results of the calculations. The time and humidity increments are the same as in Example 1 (Δt = 0.25 h, ΔW = 0.004), and thus after the first time step the moisture distribution in the crossflow dryer is the same as in the batch-in-bin dryer of Example 1 (see Table 5). The distribution after $2\Delta t$ (0.50 h) of drying in the crossflow dryer is found by repeating the calculation procedure performed at $1\Delta t$. This procedure is continued until the average of the moisture contents in the sub-layers has reached the required value (0.17 in Example 2).

Table 6 shows that after 1 hour of crossflow drying maize reaches an average moisture content of 0.17. From equation (11) it can be calculated that the throughput of the dryer is 920 kg of dry matter per hour or about 1080 kg of dried maize per hour. The moisture content of the corn exiting the dryers ranges from 0.15 to 0.19 (d.b.)

7. Conclusions

A simplified calculation method is presented for calculating the capacity and the outlet moisture content of maize in high-temperature batch-in-bin and crossflow dryers. The calculation error is within 10% of the experimental (and simulation) results.

Notation

c	specific heat, kJ kg^{-1} C^{-1}
D	width of grain column, m
G, G'	grain or airflow rate, kg dry matter m^{-2} h^{-1}
H	thickness of the grain column, m
h	enthalpy, kJ kg^{-1}
k	drying constant, h^{-1}
L	length of grain column, m
M	moisture content, dry basis (decimal)
P	point on psychrometric chart
Q	dryer capacity, kg wet grain h^{-1}
T	air temperature, C
W	humidity ratio of air, kg kg^{-1}

X height of the grain column, m

Y width of the grain column, m

t time, h

q grain temperature, C

f relative humidity, %

r density, kg dry matter m^{-3}

Δ increment (prefix)

Subscripts

a air

e equilibrium

f final

g grain

i, in inlet

o, out outlet

w water

References

ASAE, 1998. Moisture relationships of plant-based agricultural products. Data D 245.50095, American Society of Agricultural Engineers, St. Joseph, MI.

Brooker, D. B., F. W. Bakker-Arkema and C. W. Hall. 1992. *Drying and Storage of Grains and Oilseeds.* Van Nostrand Reinhold, New York, NY.

Gustafson, R. and R. V. Morey. 1981. Moisture and quality variations across the column of a crossflow dryer. *Transactions of the ASAE* 24(6) 1621-25.

Pabis, S. and S. M. Henderson. 1961. Grain drying theory: II. A critical analysis of the drying curve of shelled maize. *J. Agric. Eng. Res.* 6(2) 272-277.

Acknowledgements

The authors thank the Crop and Food Bioprocessing Center, Michigan State University, and the ffi Corporation, Indianapolis, Indiana, for the financial support of this project.

Table 1. Comparison of the experimental (Gustafson and Morey, 1981) and hand-calculated average moisture content of a batch-in-bin maize dryer*; drying time = 1.5 hours.

Drying air temp., ^{o}C	93	93	116
Initial MC, % w.b.	31.0	25.9	30.5
Experimental average MC, % w.b.	14.9	11.7	12.4
Calculated average MC, % w.b.	15.4	10.4	10.2
Error, % w.b.	0.5	-1.3	-2.2

***Grain-layer thickness 0.305 m; airflow 80 m^3 $min^{-1}tonne^{-1}$**

Table 2. Comparison of hand-calculated and simulated capacity of a crossflow maize dryer.*

Drying air temp., ^{o}C	90	90
Inlet MC, % w.b.	20	25
Hand-calculated capacity, kg h^{-1}	1246	651
Simulated capacity, kg h^{-1}	1152	590
Relative error, %	8.1	9.4

***Column dimensions (5 x 1 x 0.3)m^3; airflow 80 $m^3min^{-1}tonne^{-1}$**

Table 3. Effect of the values of Δt and ΔW on the hand-calculated final moisture content of maize dried in a crossflow dryer operating at the conditions tabulated in Table 4.

Time increment Δt , h	0.250	0.250	0.125	0.125
Humidity ratio increment ΔW , kg kg^{-1}	0.004	0.002	.004	0.002
Final MC, d.b.	0.177	0.173	0.170	0.166

Table 4. Operating conditions of the batch-in-bin and crossflow maize-drying systems of Examples 1 and 2.

Airflow rate	G_a = 1041 kg m^{-2} h^{-1}
Inlet air temperature	T_1 = 90 ^{o}C
Initial maize moisture content	M_i = 0.25 d.b.
Initial maize temperature	q_i = 20 ^{o}C
Ambient air temperature	T_o = 20 ^{o}C
Ambient relative humidity	f_o = 70%
Thickness of grain layer	H = 0.30 m
Side area of grain bed	X by Y = 5m x 1m

Table 5. Results, obtained with the simplifying calculation procedure*, of the average moisture content of maize after drying for 15 minutes in a batch-in-bin system operating at the conditions tabulated in Table 4.

Parameter	Sub-layer					Average MC dec., d.b.	Note
	1	2	3	4	5		
T, ^{o}C	90	76	62	48	34		Fig. 3
M_e, d.b.	0.014	0.025	0.044	0.075	0.180		Fig. 3
k, h^{-1}	0.878	0.645	0.461	0.320	0.215		Fig. 3
ΔH, cm	3.64	5.06	7.56	12.58	1.16		Eqns. 5,9
$e^{-k\Delta t}$	0.803	0.851	0.891	0.923	0.948		
M_f, d.b.	0.203	0.217	0.228	0.237	0.246		Eqn. 1
$H \times M_f$	0.74	1.10	1.72	2.98	0.29	0.227	Eqn. 10

* ΔW = 0.004 kg kg^{-1}; assuming q_f = 50 ^{o}C; f_{out} = 60%

Table 6. Results, obtained with the simplifying calculation procedure, of the moisture content distribution and the average moisture content of maize dried in a crossflow dryer, operating at the conditions tabulated in Table 4.

Step	Parameter	Sub-layer					Ave. MC (dec., d.b.)	Note
		1	2	3	4	5		
1	T, °C	90	76	62	48	34		Fig. 3
2	Me, d.b.	0.014	0.025	0.444	0.075	0.180		Fig. 3
3	k, h^{-1}	0.878	0.645	0.461	0.320	0.215		Fig. 3
4	$e^{-k\Delta t}$	0.803	0.851	0.891	0.923	0.948		
drying time t = 0.25 h								
5	M_i, d.b.	0.250	0.250	0.250	0.250	0.250		Initial MC
6	M_f, d.b.	0.203	0.217	0.228	0.237	0.246		Eqn. 1
7	H, cm	3.64	5.06	7.56	12.58	1.16		Eqns. 5, 9
8	$H \times M_f$	0.74	1.10	1.72	2.98	0.29	0.23	Eqn. 1
drying time t = 0.50 h								
9	M_i, d.b.	0.23	0.23	0.23	0.23	0.23		from step 8
10	M_f, d.b.	0.19	0.20	0.21	0.22	0.22		
11	H, cm	4.03	5.63	8.49	11.84	0.00		
12	$H \times M_f$	0.75	1.11	1.76	2.55	0.00	0.21	
drying time t = 0.75 h								
13	M_i, d.b.	0.21	0.21	0.21	0.21	0.21		from step 12
14	M_f, d.b.	0.17	0.18	0.19	0.20	0.20		
15	H, cm	4.49	6.30	9.63	1.87	0.00		
16	$H \times M_f$	0.75	1.13	1.81	1.87	0.00	0.19	
drying time t = 1.00 h								
17	M_i, d.b.	0.19	0.19	0.19	0.19	0.19		from step 16
18	M_f, d.b.	0.15	0.16	0.17	0.18	0.19		
19	H, cm	5.02	7.10	11.00	6.89	0.00		
20	$H \times M_f$	0.76	1.15	1.87	1.22	0.00	0.17	

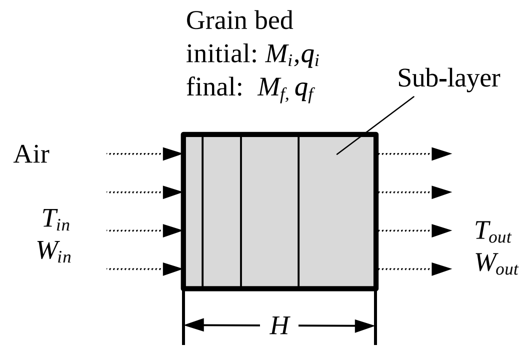

Fig. 1. Grain bed and sub-layers.

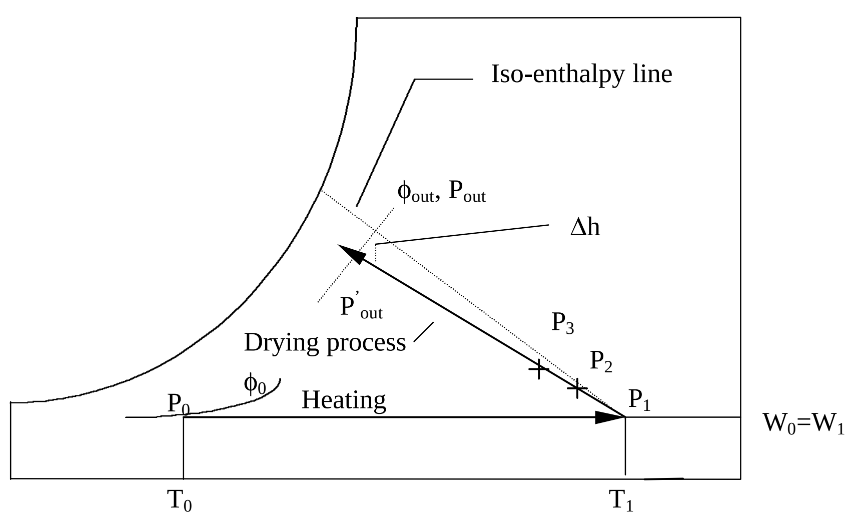

Fig. 2. Drying process on psychrometric chart.

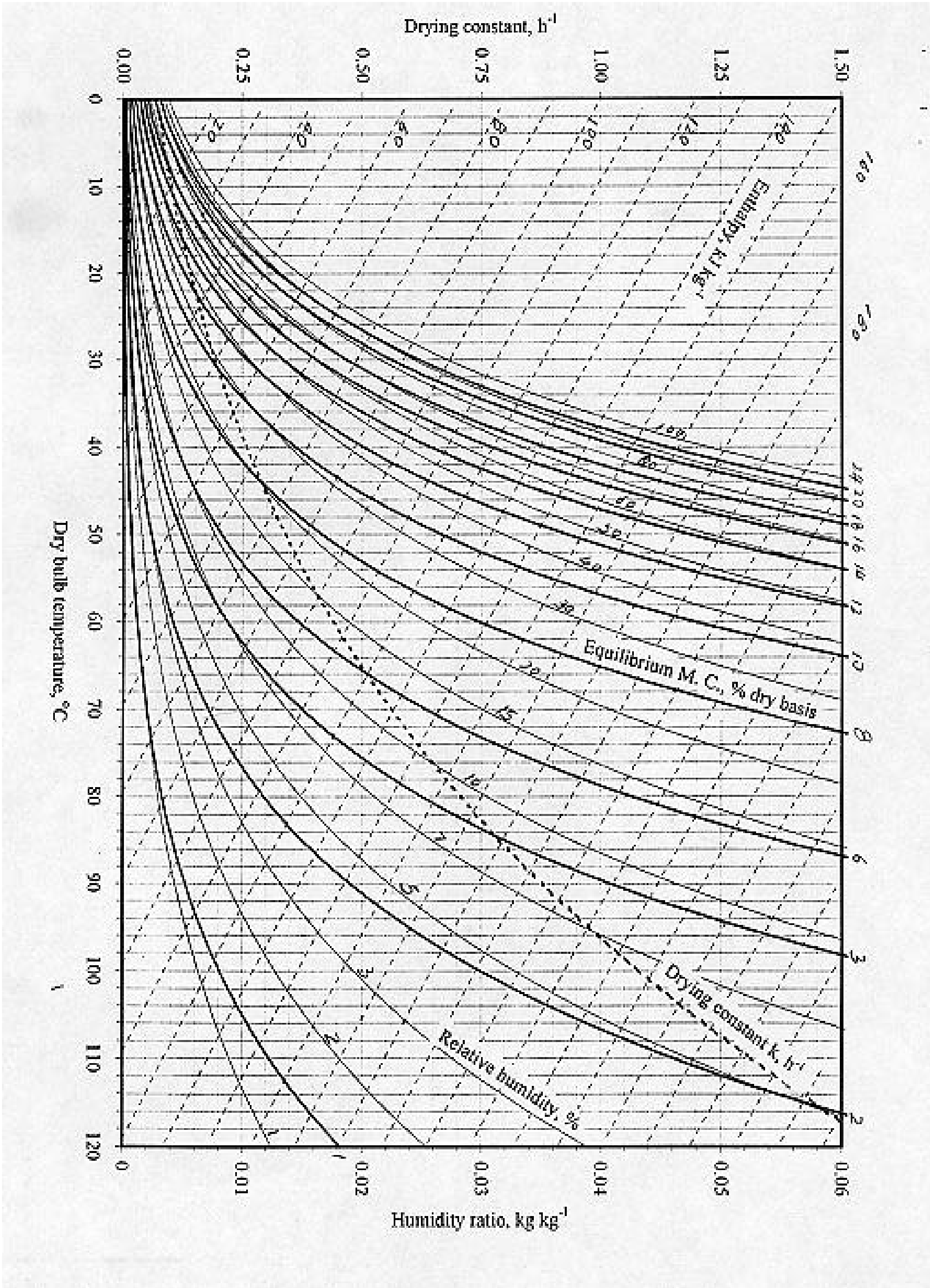

Fig. 3. Calculation chart for maize.