Design chart for in-store maize drying under tropical climates

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Abstract

Product quality, drying capacity and energy consumption have to be taken into consideration in drying system design. Long periods while in-store drying maize may cause product deterioration due to successive fungi, aflatoxin and dry matter loss. Determination of air flow rate and depth of grain is usually a problem due to the time-consuming calculation process. The objective of this study is to demonstrate the development of a design chart for in-store maize drying under tropical climates. A near equilibrium drying model was developed that included the effects of heat and moisture from respiration to improve accuracy. The model was finalised by being incorporating a submodel for aflatoxin development. Simulation results given various conditions were used to construct four quadrant charts. Minimum specific airflow rates (m^3/minute/m^3 of grain) which corresponded to a dry matter loss of 0.5 % were derived. It was observed that corresponding aflatoxin concentration were lower than 50 ppb. The minimum specific airflow rate increased with initial moisture content but decreased with bed thickness. Other critical values such as pressure drop, specific energy consumption and drying time could also be obtained from the charts. These charts are expected to be useful for design engineers to reduce calculation time and to help select the appropriate design and operating parameters for in-store maize drying.

Introduction

Methods of grain drying may include continuous flow and fixed bed. In-store drying is one method of fixed bed drying without grain movement during drying and storage. Grain is dried slowly with ambient air or air at a temperature a few degrees higher than ambient. Design of in-store drying includes selection of items such as thickness of grain bed, airflow rate, size of fan and air duct, and drying time. In addition, energy consumption, dry matter loss due to respiration, and toxic substances produced during drying and storage have to be considered. These values depend on initial moisture content of grain and ambient air parameters. Complex mathematical models and computer programs as well as a trained personnel are needed for the design. It also takes time to investigate appropriate design and operating parameters. A design chart furnished with adequate information would be useful.

Mathematical grain drying models can be classified as non-equilibrium, i.e. no equilibrium between product and drying air (Brooker et al. 1974), near-equilibrium, which assumes thermal equilibrium between product and drying air (Bakker Arkema et al. 1977; Thompson et al. 1968) and equilibrium models. The second model predicts a slightly faster drying than the first, but requires much less computer time. The last model is appropriate only to slow drying with ambient air and can provide only the position not the shape of drying zone. In in-store drying, energy input to the drying system is for the fan only. Therefore, calculation of air temperature rise while flowing across the fan and air passage is very important because it significantly affects the drying rate (Soponronnarit 1988). In some cases, especially drying of high moisture grain, heat and moisture liberated by respiration should be included in the model because this significantly improves the accuracy of the model (Soponronnarit and Chinsakolthanakorn 1990).

The main parameters of grain quality are moisture content and other physical properties such as degree of breakage, colour, and foreign matter. In the case of maize, aflatoxin is also considered, but we can find no equations describing development of aflatoxin.

The objective of this paper is to develop a mathematical model able to describe drying of high moisture maize under hot, humid climates. Also, design charts are developed from simulation results.

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Materials and Method

Mathematical drying model

The development of a drying model accommodating equations covering drying rate, energy and mass conservation, enthalpy change of air while flowing across a fan, dry matter loss and heat and moisture liberated from respiration process was presented by Soponronnarit (1988) and Soponronnarit and Chinsakolthanakorn (1990). Details are as follows :

1. Energy conservation for a thin layer

$$c_a T_o + (2502 + c_v T_o) W_o + R c_{pw} TP_o = c_a T_f + (2502 + c_v T_f) W_f + R c_{pw} T_f \quad (1)$$

where
C = specific heat, kJ/kg°C
T = air temperature,°C
TP = grain temperature,°C
W = absolute humidity, kg H_2O/kg dry air
R = ratio of dry grain mass to dry air mass, kg dry matter/kg dry air
and subscripts
a = dry airp
w = wet grain
f = after drying
v = water vapour
o = before drying

2. Mass conservation for a thin layer

$$W_f - W_o = (M_o - M_f) R \quad (2)$$

where
M = grain moisture content, decimal dry-basis.

3. Thin layer drying

The thin layer drying equation developed by Westerman et al. (1973) was manipulated. It is valid for temperature and relative humidity ranges of 38-71°C and 10–60%, respectively.

4. Energy balance at the fan

$$\dot{m}(c_a + c_v W_o)\Delta T_f = \dot{m}P / \rho_a \eta_f \quad (3)$$

where

$\dot{m}$ = mass flow rate of dry air, kg / second
ΔT_f= temperature rise by the fan, °C
ρ_a= density of dry air, kg/m^3
P = total pressure Pa
η_f= fan efficiency, decimal

5. Dry matter loss, heat and moisture from respiration

The equations of dry matter loss developed by Thompson (1972) and Steele (1967) were manipulated. Heat and moisture liberated from respiration was calculated by the following equations (Soponronnarit and Chinsakolthanakorn 1990).

$$\Delta T_h = 15778\ DML/c_{pw} \quad (4)$$
$$\Delta M_h = 0.6\ DML \quad (5)$$

where
ΔT_h = temperature rise of grain, °C
ΔM_h = moisture rise of grain, decimal dry-basis
DML = dry matter loss, decimal

In order to make the calculation possible, it is necessary to employ state equations of moist air. In this paper, the equations developed by Wilhelm (1976) were manipulated.

6. Development of aflatoxin

Aflatoxin is developed by fungi under favourable conditions. Experiments on the development of aflatoxin in maize stored in plastic bags of about 10 kg under room conditions in Bangkok were conducted by Kawashima et al. (1990). It was found that aflatoxin concentration increased with initial moisture content of grain and storage time. The development of equations describing the development of aflatoxin and employing these data will be explained in the next section.

Experiment

To verify the accuracy of the mathematical model, eight test runs of maize drying were conducted in a bin with a diameter of 0.75 m. The height of the grain bed was 1.4 m. Grain moisture content was measured at 20 cm interval by using air oven at 103°C for 72 hours. Temperature was also measured at the same positions, using type K thermocouples (±1°C) connected to a data logger. Air velocity was measured by a hot wire anemometer.

Initiative for constructing design charts

A design chart was constructed to overcome the inconveniences mentioned in the introduction to this paper. For this study, design charts for in-store maize drying under tropical climates were developed. It was assumed that grain maintained its quality if dry matter loss during drying was less than 0.5%. Therefore, the dry matter loss was kept at 0.5% for each computer simulation run. Final moisture content was assumed to be 14% wet-basis. As a result, the airflow rate corresponding to the dry matter loss of 0.5% was the minimum value for maintaining grain quality. In addition, system pressure drop was calculated (must be less than 1500 Pa) by assuming that it was 1.5 times the pressure drop in the grain bed. The pressure drop data for popcorn developed by Shedd (1953) were manipulated for this calculation. In addition, drying time and specific energy consumption were computed. These values depended on the thickness of grain bed and initial grain moisture content. Simulation results were then used to construct four quadrant design charts.

Results and Discussion

Equation of aflatoxin

Figure 1 shows the result of curve fitting using empirical equations which can be written as follows:

$$AFB_1 = A_1 + A_2 t + A_3 t^2 + A_4 t^3$$

where

$$A_1 = -3031.360 + 248.7328M_w - 4.917356(M_w)^2 \quad (6\alpha)$$
$$A_2 = 2512.535205.0159M_w + 4.022257(M_w)^2$$
$$A_3 = 544.2637 + 44.03857M_w 0.8539792(M_w)^2$$
$$A_4 = 22.918111.856915M_w + 0.03609485(M_w)^2$$

and
AFB_1= aflatoxin concentration (B_1), ppb
t = storage time, day
M_w = moisture content, % wet-basis

The above equation is valid for moisture contents ranging from 20.7 to 28.9% wet basis and appropriate only for hot ambient air (about 25–35°C). If the value of AFB_1 or $d(AFB_1)/dt$ from equation (6a) was negative, the value of $d(AFB_1)/dt$ was made zero. In case of moisture content below 20.7% wet-basis,

$$AFB_1 = 0 \quad (6b)$$

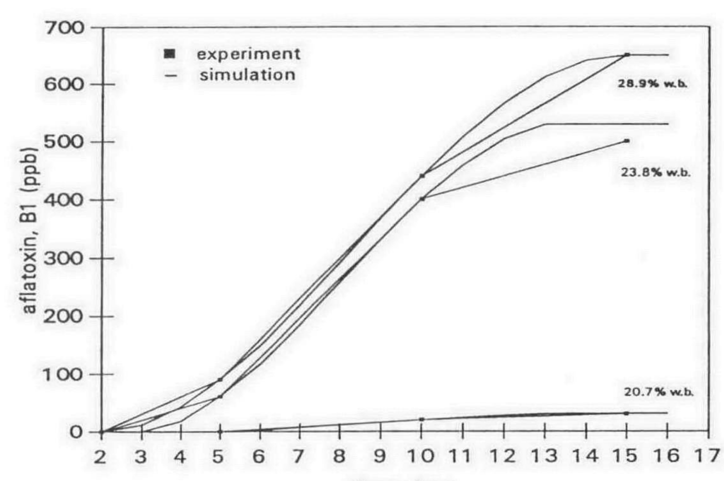

Fig. 1. Evolution of simulated and measured aflatoxin concentration.

Comparison between experimental and simulated results

Figure 2 shows comparative results of experiment and simulation. The latter can be divided into simulation with and without heat and moisture from respiration. It was found that the accuracy of the model was improved when heat from respiration was included especially at the top layer which was dried latest. In case of lower initial grain moisture content (not

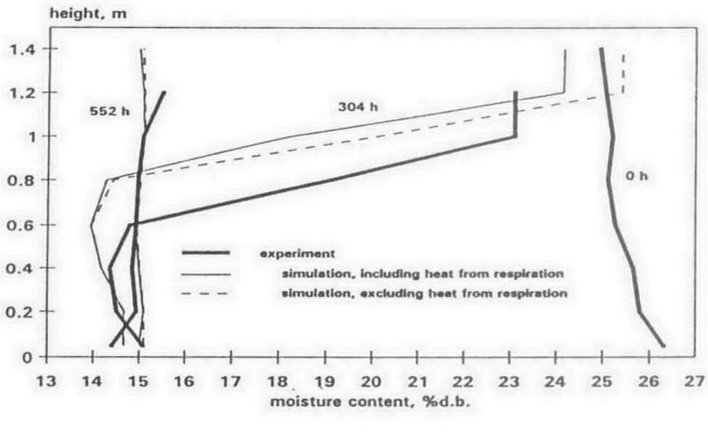

Fig. 2. Simulated and measured moisture profiles, test no. 4, December 1991.

shown in this paper), there was no difference between the two cases. This was due to lower respiration in drier grain.

Design chart

Figure 3 shows the simulation results for continuous ventilation, using ambient air conditions of September 1988, which is the worst month during the 5-year period, in four quadrant chart. Final moisture content was 14% wet-basis and dry matter loss was 0.5%. It was found that aflatoxin concentration was lower than 50 ppb in all simulation runs presented in the chart. Minimum airflow rate increased along with initial grain moisture content, but decreased with bed depth. Other important values such as pressure drop, drying time and energy consumption, are also evident. Figure 4 shows the simulation results using ambient air condition of September 1992 which is the best month during the 5-year period. It was similar to the previous case except that energy consumption increased along with initial moisture content. In the former case, energy consumption increased with initial moisture content at low level, to be reversed at high moisture levels. At higher initial moisture content, temperature rise by the fan was higher due to higher airflow rate and thus improved drying potential significantly especially for poor weather as in the former case.

Figures 5 and 6 show the simulation results of intermittent ventilation corresponding to Figures 3 and 4, respectively. They are similar to Figure 4. Minimum airflow rates were a little higher but energy consumption decreased significantly especially for the case of poor weather. Figures 7 and 8 show the evolution of corresponding ambient temperature and relative humidity.

Conclusion

The following conclusions can be drawn from this paper:

1. The mathematical model was accurate and was improved when heat and moisture liberated from respiration were included, especially for the case of high initial grain moisture content.

2. The design charts may be useful to designers of in-store maize drying under hot, humid climates. They help select appropriate design and operating parameters.

3. From the design charts, it may be concluded that in-store maize drying under hot, humid climates is feasible provided that initial grain moisture content is not so high as to necessitate reducing grain depth to the extent that storage may not be economical.

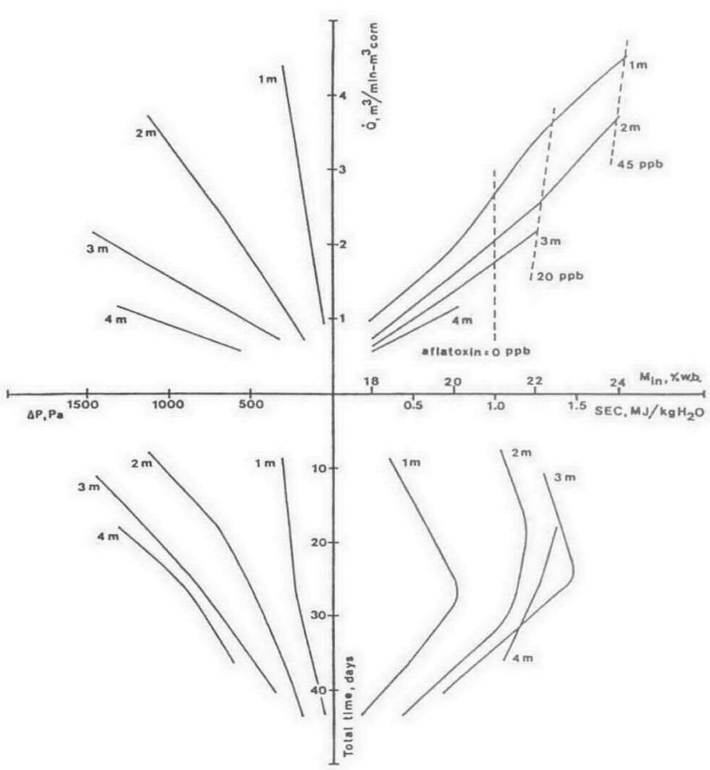

Fig. 3. Design chart for in-store maize drying (continuous ventilation), ambient mean temperature = 28.2°C, ambient relative humidity = 81.5%, dry matter loss = 0.5%. M_{in} = initial moisture content; Q = airflow rate for 0.5% dry matter loss; ΔP = total pressure drop; SEC = specific energy consumption.

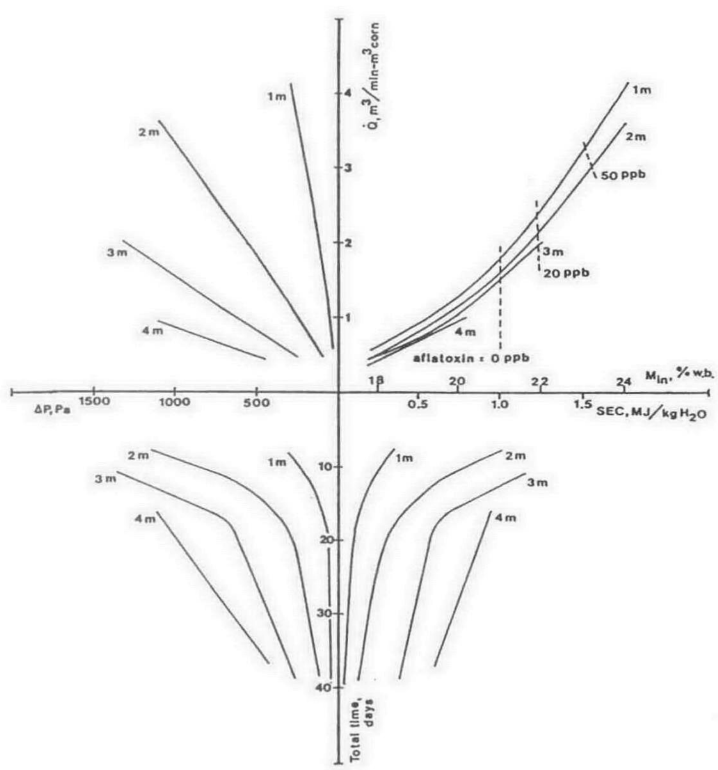

Fig. 4. Design chart for in-store maize drying (continuous ventilation), ambient mean temperature = 28.4°C, ambient relative humidity = 77.8%, dry matter loss = 0.5%. M_{in} = initial moisture content; Q = airflow rate for 0.5% dry matter loss; ΔP = total pressure drop; SEC = specific energy consumption.

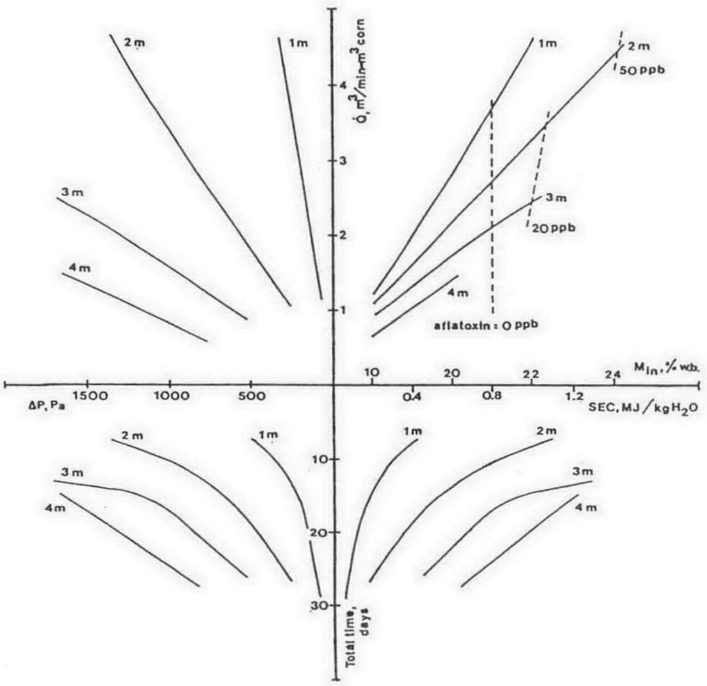

Fig. 5. Design chart for in-store maize drying (intermittent ventilation), inlet relative humidity below 75%, ambient mean temperature = 28.2°C, ambient relative humidity = 81.5%, dry matter loss = 0.5%. M_{in} = initial moisture content; Q = airflow rate for 0.5% dry matter loss; ΔP = total pressure drop; SEC = specific energy consumption.

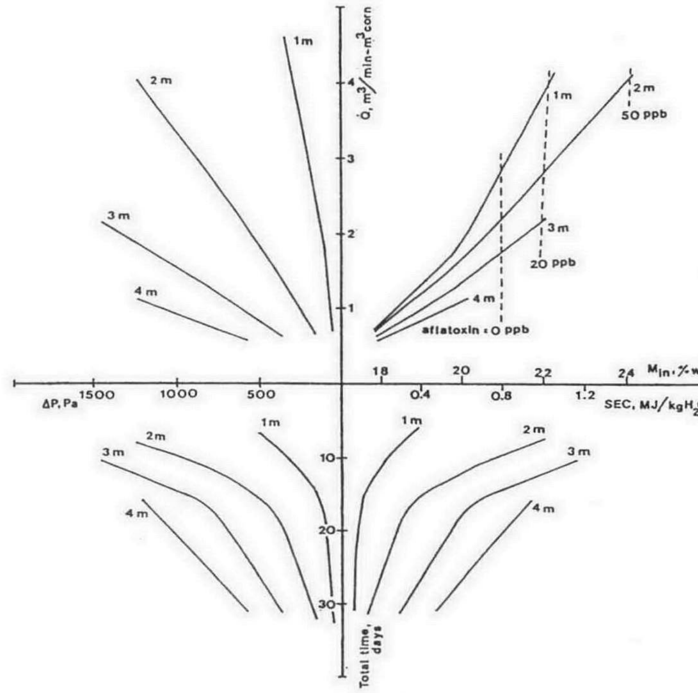

Fig. 6. Design chart for in-store maize drying (intermittent ventilation), inlet relative humidity below 75%, ambient mean temperature = 28.4°C, ambient relative humidity = 77.8%, dry matter loss = 0.5%. M_{in} = initial moisture content; Q = airflow rate for 0.5% dry matter loss; ΔP = total pressure drop; SEC = specific energy consumption.

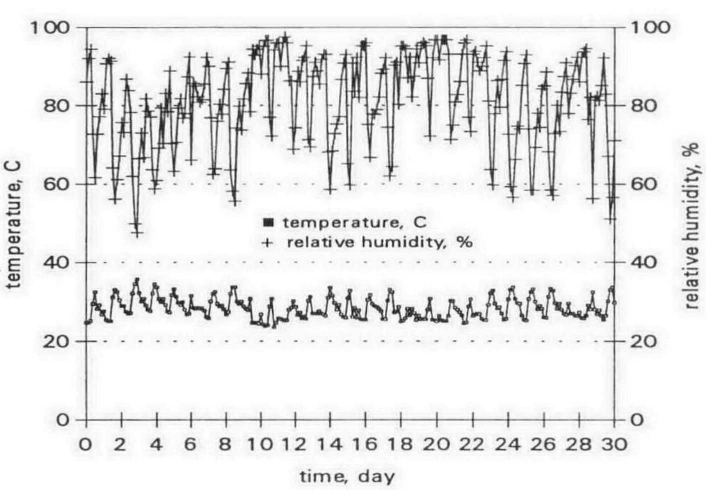

Fig. 7. Evolution of ambient air temperature and relative humidity, September 1988.

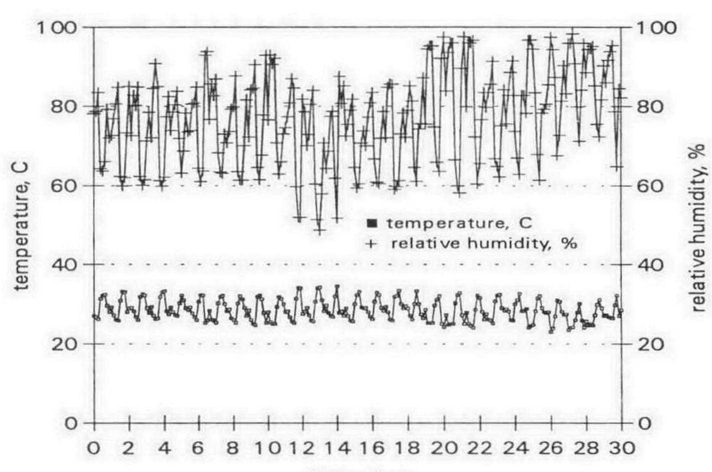

Fig. 7. Evolution of ambient air temperature and relative humidity, September 1992.

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