Applications of MATLAB-based software to drying simulation

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Abstract

The quality of grain drying depends on an adequate control of drying parameters. The flow rate, temperature and relative humidity of drying air play major roles in grains drying. Drying simulation is based on plenty of parameters with sequent time series. It needs a powerful algorithmic tool to process such masses of mathmatic data. A software-based simulation was proved to be more efficient and economic for predicting the drying results. Based on previous surveys, lots of equations concerning air psychromatrics, thin layer drying, air flow resistance, equilibrium moisture content, deep bed drying are combined to develope a software for drying simulation.

This study develops a MATLAB-based software SAPGD-2004 to predict the air properties, psychrometrics data, air flow resistance, equilibrium moisture contents, the results of thin layer drying and deep-bed drying. The study also examines thin layer drying equations in ASAE Standard S448.1(2003) and other literatures. Some errors, however, were found during verifying with simulations. The software was proved to be a convenient tool to identify the range of applicability and potential uncertainties for these equations.

Key Words: psycrometrics, airflow resistance, equilibrium moisture content, thin layer drying, deep-bed drying, simulation, grain drying, MATLAB.

1. INTRODUCTION

Grain drying plays an important role in post-harvesting of crops. Grains are harvested in high moisture, then dried and stored in bins before milling process. During the drying and storage periods, the ambient conditions can affect the grain quality. Traditionally, psychrometric charts are the tools to be used for engineers. But it was inconvenient and limited by the shortage of its estimating error and low detecting speed. Theoretical and empirical equations were derived by previous researchers[1,5]. Psychrometric properties of moist air, such as dry (wet) bulb temperature, relative humidity, humidity ratio, dew point temperature, specific volume and enthalpy, are usually needed and calculated in a tedius manner. The properties of drying air decides the equilibrium moisture content and the removing capacity of water in grain. The air flow affects significantly the drying rate and air flow resistance through the grain bed which is the major criterion in designing the ventilation system. Equilibrium moisture content under certain ambient properties determines the last period of the thin layer drying, which is a fundation of deep-bed drying or circulating drying.

Researchers have developed experimentally a number of these related equations for many crops. ASAE [1,2,3,4] summarizes a group of these equations under ASAE Standard-2003 S448.1 JUL01, D272.3 DEC01, D271.2 DEC99, D245.5 JAN01.

Simulation of drying needs simultaneous algorithm of enormous equations. MATLAB [35] is an interactive program and technical computing environment with numeric computation and data visualization. It provides integrated numerical analysis, matrix computation, signal processing, and graphics in an easy-to-use environment where problems and solutions are easily expressed without complicated programming. Instead of operating complex loop mathematics, a matrix-oriented calculation saves execution time on PCs. Besides, its plotting facilities, such as "PLOT", "LOGLOG", "MESH" are powerful in handling massive data and graphics. The "UICONTROL" command also plays a crucial role in constructing an interactive window with graphic user interface (GUI).

The aims of this study are summarizing empirical equations related to grain drying for most grains and a MATLAB-based program, entitled SAPGD-2004 (Simulation of Air Properties and Grain Drying, Version 2004), was developed, in which thin layer drying equations can be checked visually for their range of applicability and any potential uncertainty in the equations.

2. REVIEW OF RELATED EQUATIONS

2.1 Psychrometric Data

ASHRE[5] and ASAE[1] summarized the previous research concerned with psychrometrics. Some interactive computer programs for simulation of psychrometrics [15,17,38] were known to be executed under DOS and WINDOWS. Functions included in this study are listed as follow.

Saturated vapor pressure, P_{ws}

$$\ln(P_{ws})=C_1/T_{db}+C_2+C_3T_{db}+C_4T_{db}^2+C_5T_{db}^3+C_6T_{db}^4+C_7\ln(T_{db}),\quad 173.16\ K\leqq T_{db}\leqq 273.16\ K \quad (1a)$$

$$\ln(P_{ws})=C_8/T_{db}+C_9+C_{10}T_{db}+C_{11}T_{db}^2+C_{12}T_{db}^3+C_{13}\ln(T_{db}),\quad 273.16\ K\leqq T_{db}\leqq 473.16\ K \quad (1b)$$

$C_1 \sim C_{13}$ are constants [5] and T_{db} is the dry bulb temperature.

Dew point temperatre [17], T_{dp}

$$T_{dp}=237.203-1.8726\,\alpha+1.1689\,\alpha^2 \qquad 273.16\ K\leqq T_{dp}\leqq 343.16\ K \quad (2a)$$

$$T_{dp}=212.71+7.0322\,\alpha+0.3700\,\alpha^2 \qquad 213.16\ K\leqq T_{dp}\leqq 273.16\ K \quad (2b)$$

P_v is vapor pressure in Pa and $\alpha=\ell n\,(P_v/1000)$.

Latent heat [1] of sublimation (h_{ig}) or vaporization (h_{fg}) at saturation, J/Kg

$$h_{ig}=2{,}839{,}683.144-212.56384\times(T_{db}-255.38) \qquad 255.38\ K\leqq T_{db}\leqq 273.16\ K \quad (3a)$$

$$h_{fg}=2{,}502{,}535.259-2{,}385.76424\times(T_{db}-273.16) \qquad 273.16\ K\leqq T_{db}\leqq 338.72\ K \quad (3b)$$

$$h_{fg}=(7{,}329{,}155{,}978{,}000-15995{,}964.08\times T_{db}^2)^{1/2} \qquad 338.72\ K\leqq T_{db}\leqq 533.16\ K \quad (3c)$$

Enthalpy[5], H (KJ/Kg)

$H=[1.006\times T_{db}+W\times(2501+1.805\times T_{db})]$, W is humidity ratio. (4)

Vapor pressure [5] ,P_v (Pa).

$P_v=P_{atm}W/(0.62198+W)$, P_{atm} is atmospheric pressure (1 atm=1.01×10^5Pa) . (5)

Wet bulb temperature [1], T_{wb}.

$T_{wb}=(P_{swb}-P_v)/B'+T_{db}$ 255.38 K$\leqq T_{db}\leqq$533.16 K (6a)

$B'=1006.9254\times(P_{swb}-P_{atm})\times(1+0.15577P_v/P_{atm})/0.62194\times h_{fg}'$ (6b)

In which P_{swb} is the P_s calculated from equation (1a) or (1b) by substituting T_{wb} for T_{db}. (Substitute h'_{ig} for h'_{fg} where $T_{wb}\leqq$273.16 K)

Humidity ratio[1], W.

$W=0.62198\times P_v/(P_{atm}-P_v)$ 255.38 K$\leqq T_{db}\leqq$533.16 K (7a)

or $$W=\frac{(2501-2.381\times T_{db})\times W_s-(T_{db}-T_{wb})}{(2501+1.805\times T_{db}-4.186\times T_{wb})}$$ (7b)

W_s, same as W in equation [7a], is derived in terms of P_{swb} instead of P_v, and P_{atm} at T_{db}.

Degree of saturation [5], μ

$\mu=W/W_s$ (8)

Specific volume [5], V_{sa}.

$V_{sa}=287\times T_{db}(1+1.6078\times W)/P_{atm}$ 255.38 K$\leqq T_{db}\leqq$533.16 K (9)

Relative humidity [5], rh

$rh=P_v/P_s$ (10a)

$rh=\mu/[1-(1-\mu)(P_s/P_{atm})]$ (10b)

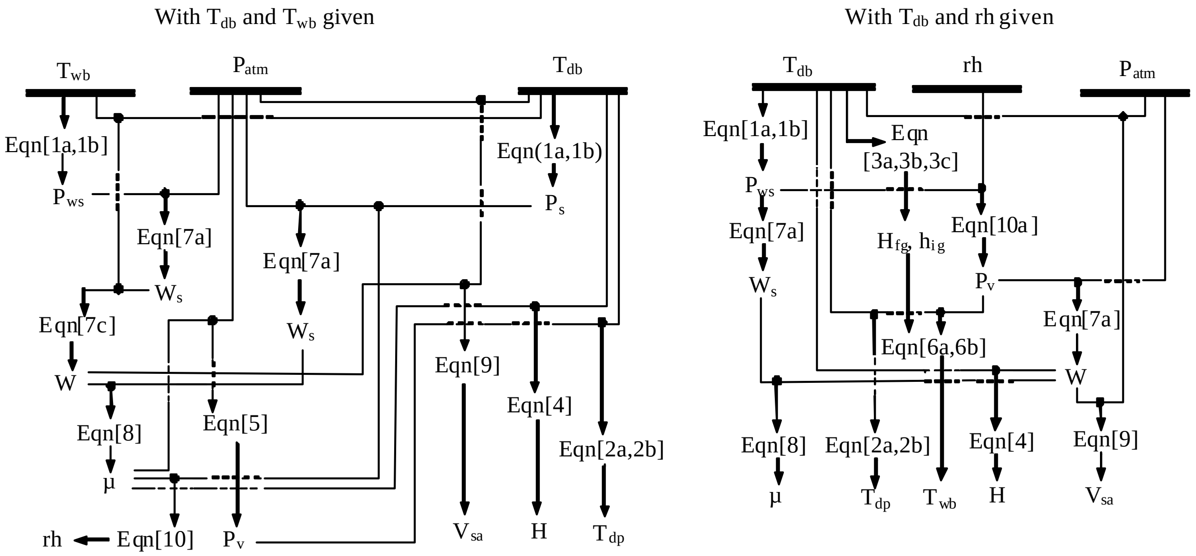

Figure 1. The categorized flow chart for calculation of psychometric data

In practice, the dry bulb and wet bulb temperatures and relative humidity are three that can easily be measured and used to form the basic input pairs to find other psychrometric information in this program. Based on looping technique, equations (1)~(10) can be applied to find some other properties for different inputs as the examples in Figure 1.

2.2 **Pressure Drop of Airflow through Grains**

$$\frac{\Delta P}{y} = \frac{AQ^2}{\log_e(1+BQ)} \tag{11}$$

ΔP: pressure drop, y : grain bed depth of certain grain layer (measured from the inlet of hot air), Q: airflow in volume rate, $m^3/s.m^2$, A B: constants listed in ASAE D273.3 DEC.01 [3]

2.3 **Thin Layer Drying of Grains**

Simplified models such as two-term models are therefore developed [18, 26] and applied for the grains such as peanuts, paddy and soybeans [22]:

$$MR = \frac{M - M_e}{M_i - M_e} = A_o \exp(-k_o t) + A_1 \exp(-k_1 t) \tag{12}$$

Where MR is moisture ratio, M the instantaneous moisture content, d.b., M_i the initial moisture content, d.b., M_e the final equilibrium moisture content, d.b. and A_o , k_o , A_1 , k_1 are empirical coefficients, while t is the elapsed drying time.

When drying process takes long enough, the one-term model will become popular in describing the drying rate:

$$MR = \frac{M - M_e}{M_i - M_e} = A_o \exp(-k_o t) \tag{13}$$

The form of Newton's law of cooling in heat transfer is often used to describe the moisture losses in thin-layer grain drying. The drying rate is proportional to the difference between the average and M_e in a solid material:

$$\frac{dM}{dt} = -k(M - M_e) \tag{14}$$

If drying constant, k, is independent of M and M_e, the equation may be integrated directly described as:

$$MR = \exp(-kt) \tag{15}$$

In this case, the resistance to moisture movement exists only at the surface of particles. This is not true, especially for a long period of drying. Generally speaking, Newton model underestimates the drying rate during the initial stages of drying and overestimates it in the final one [23]. Henderson and Pabis [19, 20], Pabis and Henderson [29] indicated that the grain temperature governs the rate of drying, which can be expressed as:

$$k=a\cdot\exp[b/(T+273)] \quad (16)$$

The a and b are coefficients. For cooling simulation, the grain temperature, T_g, is used instead of the air temperature, T, to define k value.

Page [30] modified the Newton model into the following form, the one most drying equations employ now. The n is empirical coefficient.

$$MR = \exp(-k\,t^n) \quad (17)$$

General exponential form was used for the time relationship [7, 8]. The relevant parameters can be determined by a nonlinear combined approach and expressed as following equations: (P_1~P_5 are empirical coefficients)

1-term model : $$MR = P_1 \exp(P_2\,k\,t) + (1-P_1) \quad (18)$$

2-term model : $$MR = (1-P_1)\exp(P_2 k\,t) + P_1 \exp(P_3\,k\,t) \quad (19)$$

3-term model : $$MR = (1-P_1-P_2)\exp(P_3\,k\,t) + P_1 \exp(P_4\,k\,t) + P_2 \exp(P_5\,k\,t) \quad (20)$$

Troeger and Butler [36] worked out a model on peanuts as follows, the parameters *a* and *b* both varied with moisture ratio.

$$dM/dt = a\,(M_i - M_e)\,MR^b \quad (21)$$

2.4 Equilibrium Moisture Content, M_e.

Modified Henderson equation: $$rh = 1-\exp[-A\times(T+C)\times(M_e)^B] \quad (22)$$

Modified Chung-Pfost equation: $$rh = 1-\exp[-\frac{A}{T+C}\exp(-B\times M_e)] \quad (23)$$

Modified Halsey equation: $$rh = \exp[-\frac{\exp(A+B\times T)}{(M_e)^c}] \quad (24)$$

Modified Oswin equation: $$rh = [(\frac{A+B\times T}{M_e})^C + 1]^{-1} \quad (25)$$

A, B and C are constants listed in ASAE D245.5[2].

2.5 Deep-Bed Drying With Logarithmic Model

The original equation derived [21] on the basis of heat and mass balance can be employed to simulate the stationary-bed dryers:

$$G\cdot S_a\cdot\frac{\partial T_{db}}{\partial y} = ?_g\cdot h_{fg}\cdot\frac{\partial M}{\partial t} \quad (26)$$

G is the air flow in weight rate, $Kg/m^2.hr$, S_a is the specific heat of hot air, $?_g$ is bulk density of grain. The solution [6] has been tentatively proposed in a simple form and was improved by using an exponential form:

$$MR = \frac{e^{D'}}{e^{D'} + e^{Y'} - 1} \qquad \text{(D‘ is depth factor and Y‘ is time factor)} \qquad (27)$$

In which both drying time, t, and grain depth, y, are expressed in dimensionless terms θ, D_F. The grain moisture and temperature ratios for certain drying time and bed depth, can then be calculated as follow:

$$MR(D_F, q) = \frac{e^{D_F}}{e^{D_F} + e^{?} - 1} = \frac{M - M_e}{M_i - M_e} \qquad (28)$$

$$T_g(D_F, \theta) = \frac{e^{?}}{e^{D_F} + e^{?} - 1} = \frac{T_g - T_e}{T_i - T_e} \qquad (29)$$

which $D_F = \frac{h_g \cdot k \cdot ?_g}{G \cdot S_a} (\frac{M_i - M_e}{T_i - T_e}) \cdot y, \ \theta = k \cdot t$

Drying simulations of grains and crops based on the investigated thin-layer drying equations [9, 10, 27, 37, 39] have been developed to describe the drying behaviors of fixed deep-bed shelled corn drying process [12, 13, 14] and circulating-type rice dryer [16].

3. METHOD AND DISCUSSIONS

The SAPGD-2004 program, written in MATLAB, consists of five simulations, namely, psychrometrics of moist air, the resistance of grain to airflow, EMC, thin-layer drying curves and deep-bed drying model. Each simulation can be executed by selecting options from the menu "WORK" in operating window. Some examples are explained as below:

3.1 Psychrometrics of moist air

The familiar psychrometric chart was plotted in the operating window as Figure 2 and the point of interest also shown on the chart indicated by a blue circle. The range of the temperature (X axis) can be adjusted using "Range" slider. The parameters of simulating results were demonstrated in the "Information" box.

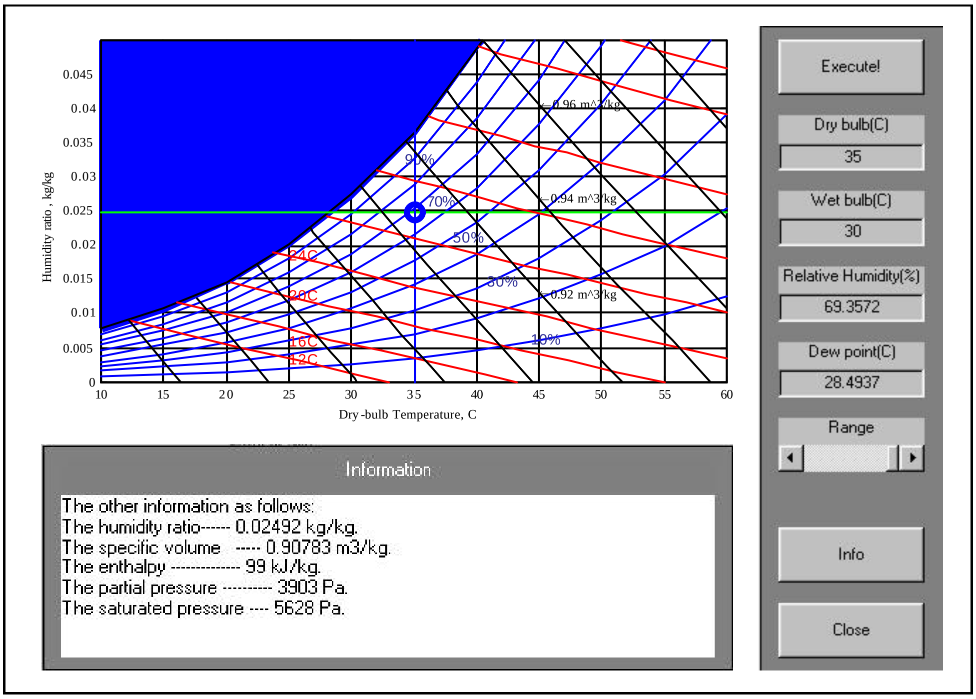

Figure 2 The operating window of "Psychrometrics of moist air"

For the sake of simplicity and practical applications, three parameters, including T_{db}, T_{wb} and rh, out of ten parameters listed in equation (1~10) are utilized as the input options because of its easy obtaining. Various thermodynamic states in psychometric chart can be described by any randomly selected two independent variables of the three parameters to derive the thermodynamic properties such as humidity ratio, specific volume, enthalpy, partial pressure, saturated pressure, absolute humidity and dew point.

Using equations of wet bulb lines, (6a) and (6b), was not able to derive T_{wb} directly. To find the root of the equation, numerical approach is required. First, predict a value T_{wb}' to evaluate the constant B' from equation (6b). Then a new T_{wb} are derived from equation (6a). The iteration algorithm continues until the convergence is minimized to its extent.

3.2 Resistance to Airflow of Grains

To simulate the resistance to airflow for different grains, both logarithmic and ordinary coordinates in vertical axis are provided as shown in Figures 3 and 4, respectively. The specific pressure drop for a single input of flow rate is also available. The red line will indicate its location of the status point. The simulation covers 39 grains, listed in ASAE Standard D272.3 [3] and provides the design references of blower and fan for dryer and silo. The applicable ranges of resistance curves are also shown in the "NOTE" box for a proper reference.

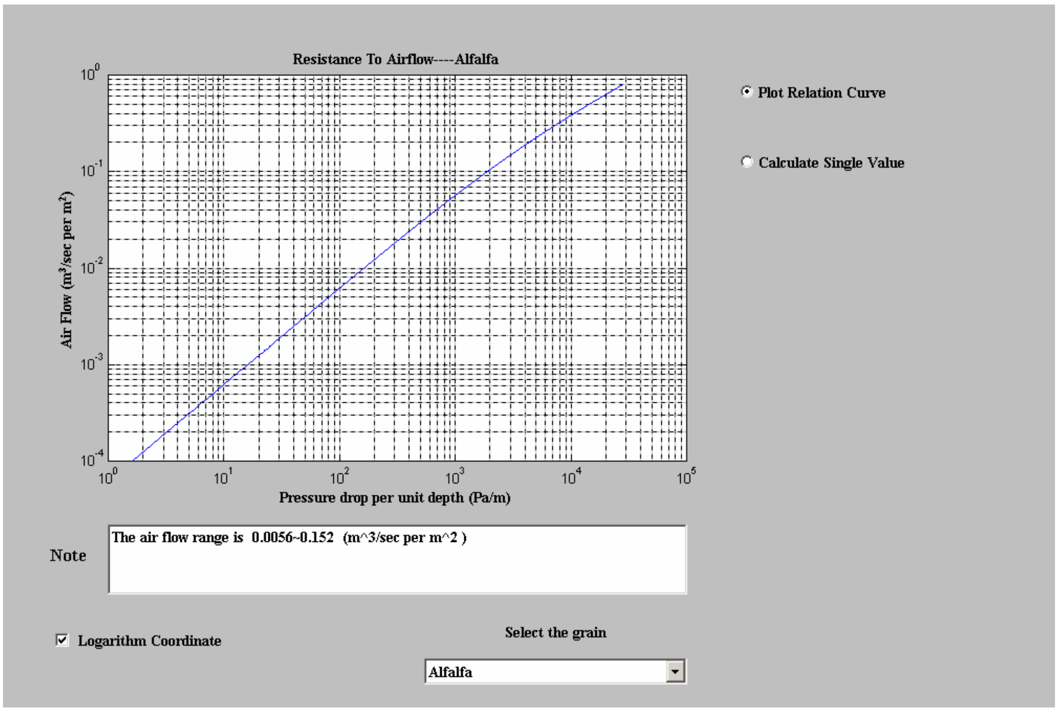

Figure 3 The grain resistance to airflow on logarithmic scales

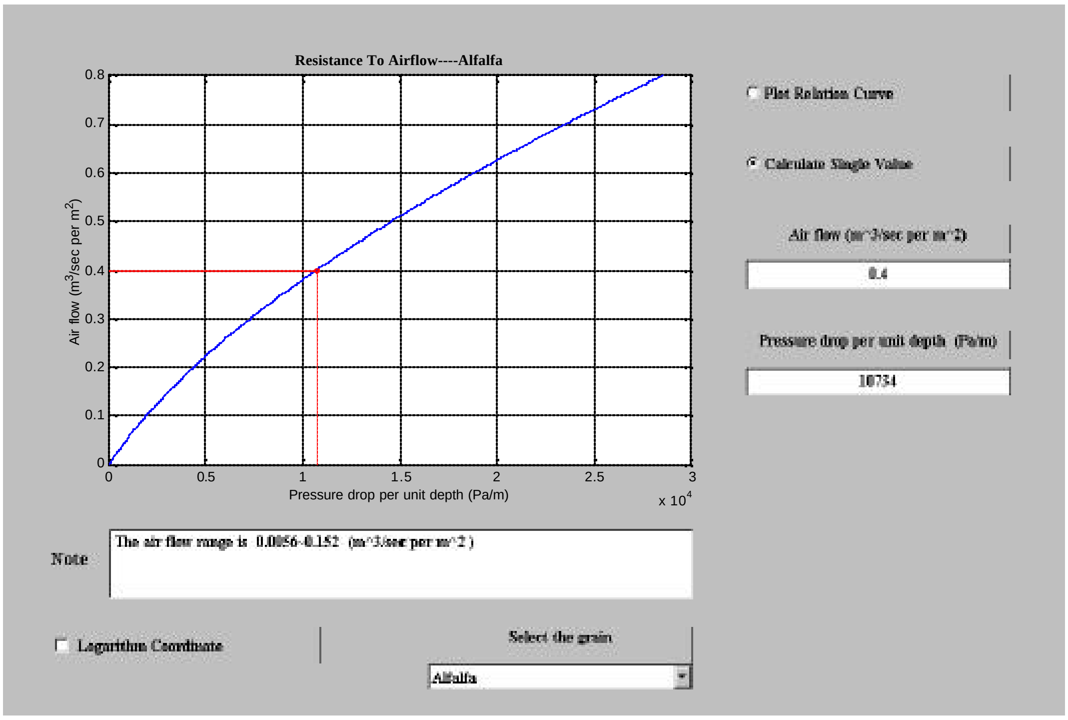

Figure 4 The pressure drop specified for single input of air flow rate on an ordinary scale.

3.3 Equilibrium Moisture Content, M_e

Numerous types of equations [11] can be used to predict the grain M_e, but in this study four are constructed for 45 grains with 97 sets of parameters, which were listed in ASAE Standard D245.5 [2]. The modified Henderson's, Chung-Pfost's, Halsey's and Oswin's models are included to cover most of the grains. In the "NOTE" box, message on the applicability of equation will also be shown, followed boxes for standard error and p value of each regressed equation will be pointed out on plotting area in Figure 5. Some equations can predict the grain moisture on the absorption basis by selecting the menu "processing method", which sometimes may be useful for storage study and such message will also be included in the "NOTE" box.

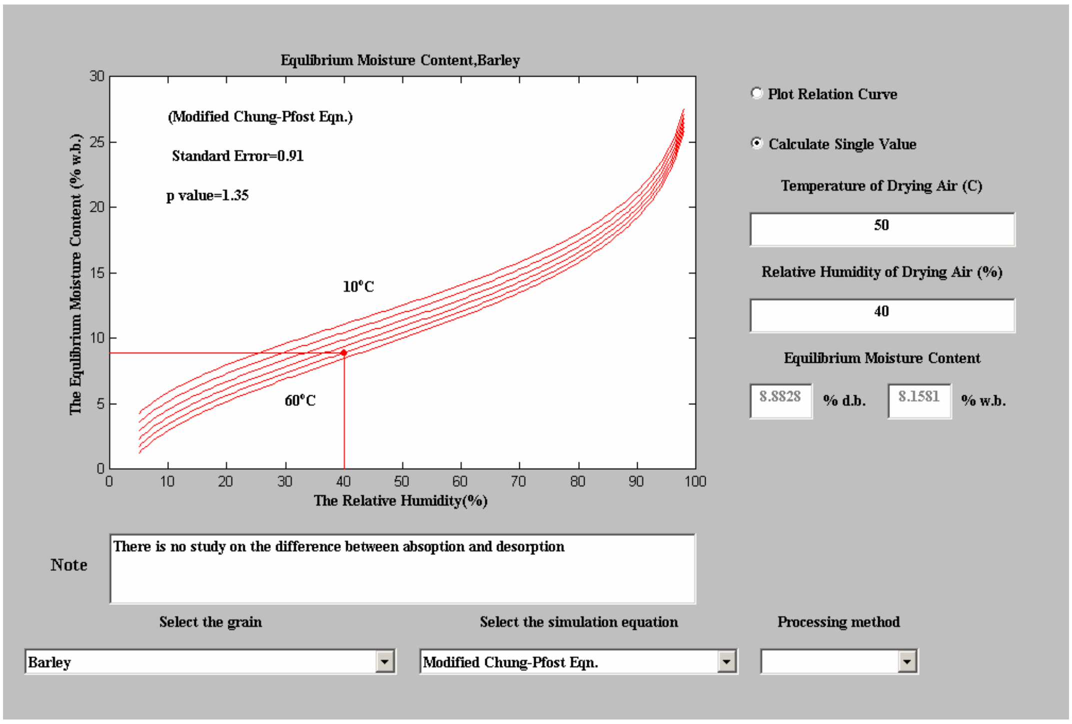

Figure 5 M_e can be shown in multiple curves.

M_e curves are plotted in a group of six with a temperature interval of 10°C in a range of 10~60°C. This program can also calculate the individual result of moisture content for specific input on ambient conditions. It is a handy feature for those require immediate precise answers for their design purposes.

3.4 Thin Layer Drying

During drying period, MR usually decreases and approaches zero with the elapsed time. In this study, the drying curves can be expressed as M or MR in terms of drying time.

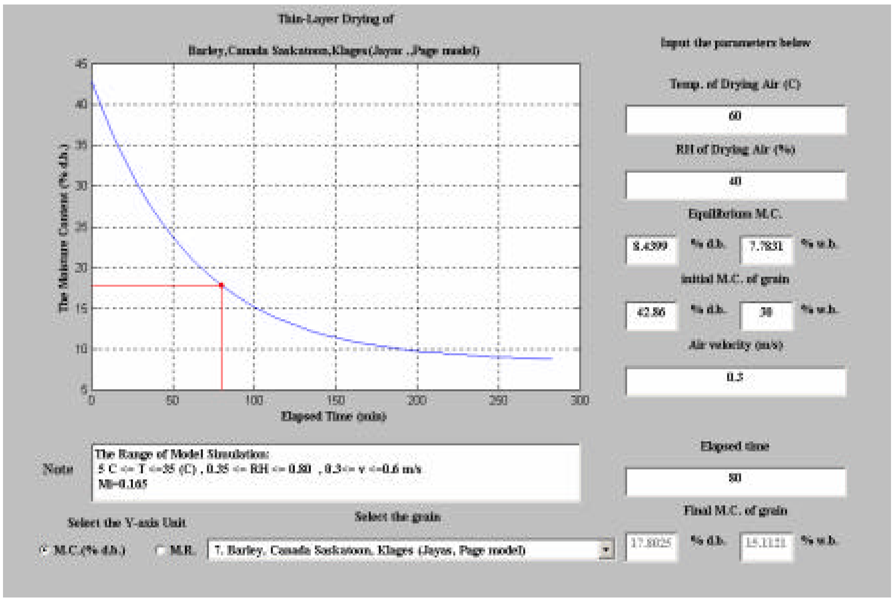

Figure 6 The simulating window for the thin-layer drying

There are 45 sets of thin layer drying equations for 17 kinds of grains summarized [39] and preconstructed in the program and can be selected from the pop-up menu (Figure 6). Once the type of grain is chosen, a corresponding thin layer drying curve will appear in the plotting area under the default conditions, including air temperature, rh, grain M_e, grain M_i and drying air velocity.

The drying time, in X axis, is expressed in the unit (hour, minute, or second) specified by the original equations. The unit of y coordinate, however, is optional for setting MR or MC(%,db). The experiment ranges defined in equations will be shown in the 'Note' box. To obtain the moisture content at a specific time, the input box is also available for this purpose and the corresponding point will also be shown on the curve.

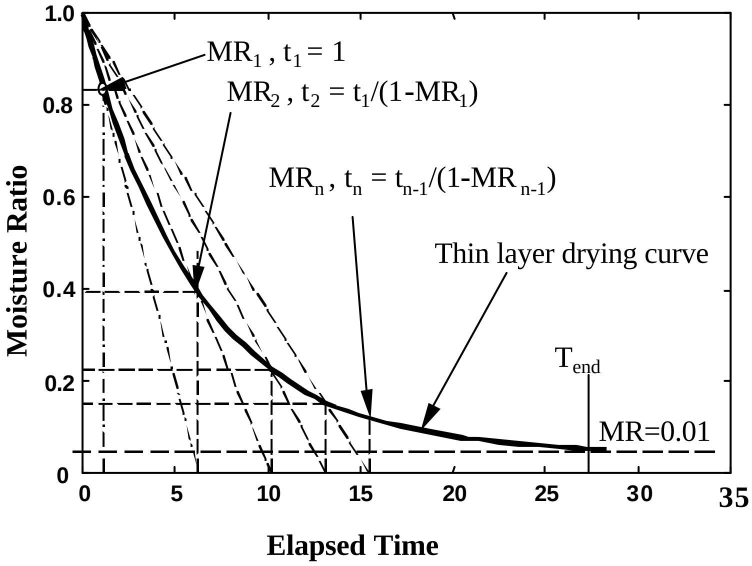

Figure 7 The iteration procedure of finding ending time for thin layer drying curve

If value of T or rh of drying air was changed, the M_e would change accordingly. The M_e can be derived from equations (22)~(25) and parameters can be found in ASAE Standard [2].

Lots of drying models composed of complicated theoretical algorithm.[31,33] In this software, most thin layer drying equations are based on Page's equation and their related parameters, obtained from empirical results. As the drying constant was regressed with experimental data for various grains, there exists certain restrictions of applicable range for practical use, as displayed in the 'NOTE ' box.

Once a grain is selected, a thin layer drying curve of the selected grain will appear in the plotting area, which is plotted according to the default drying conditions, such as air temperature, relative humidity, initial moisture content, and air velocity (if necessary). The output is displayed in the graph for either moisture ratio (decimal) or direct change of moisture content (MC db, %), if selected by hitting the radio button.

During simulation process, an ending time (t_{end}) is also required to have the proper plotting span shown in the window. An inverse analytical solution for the ending time may be required as the moisture ratio drops down to 0.01 for this study.

In some cases it is diffucult to find the analytical inverse solution for ending time. It is required to iterate in order to find the ending time quickly. Iteration procedure as shown in Figure 7 which initial points of t=0 and t=1 are assumed and iteration starts to find the closeness of the point around the specified time by the equation $t_n = t_{n-1}/(1-MR_{n-1})$ is more rapid than with fixed time interval.

Following this technique, the solution converges fast in the first half of drying curve but slows down in the second half as show in Fingure 6. Therefore, an accurate ending time can be obtained rapidly by adjusting time increment with the discrepancy of final moisture ratio.

Similar procedures have been applied [39] to compare the simulated drying equations with experimental data provided in the original papers, most of them were found to yield similar results. Evaluations were made by following the original experimental curve and overlapping it with the curve calculated and drawn using SAPGD-2004. During the process of verification, besides some typos [39], several discrepancies were found that are highlighted as follows:

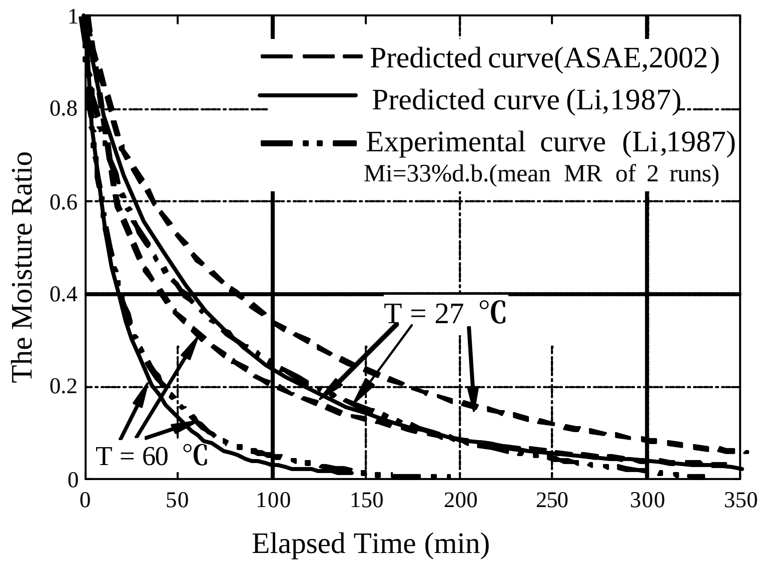

Figure 8 Predicted and experimental curves for Sunflower

The unit of moisture content in ASAE Standard [4] was defined as decimal, whereas it was percentage that Li et al. [25] adopted in sunflower equation. Accordingly, the simulated result, represented as Figure 8, shows a great discrepancy where moisture ratio calculated using decimal moisture content predicts a lower drying rate. The higher the temperature, the greater the discrepancy. Some other errors found in ASAE Standard was discussed in detail [39].

There are drying constants k and n found in each of the thin layer drying equations from (12) to (21). The inappropriate adoption of a constant into certain thin layer drying equation will cause a serious mistake which can't be easily detected. In ASAE Standard-2002 S448.1 JUL01, it was the soybeans (Cutler variety) constants k and n by Overhults et. al. [28] that was adopted, while they were wrongly applied to Page's (MR=exp $(-kt^n)$) instead of MR= exp $[-(kt)^n]$ that was found in the original research. Such a mistake, shown as following, is not easy to be detected since it happens to yield a seemingly normal exponential curve. A verification conducted in this research as shown in Figure 9 could avoid the possible serious causing errors.

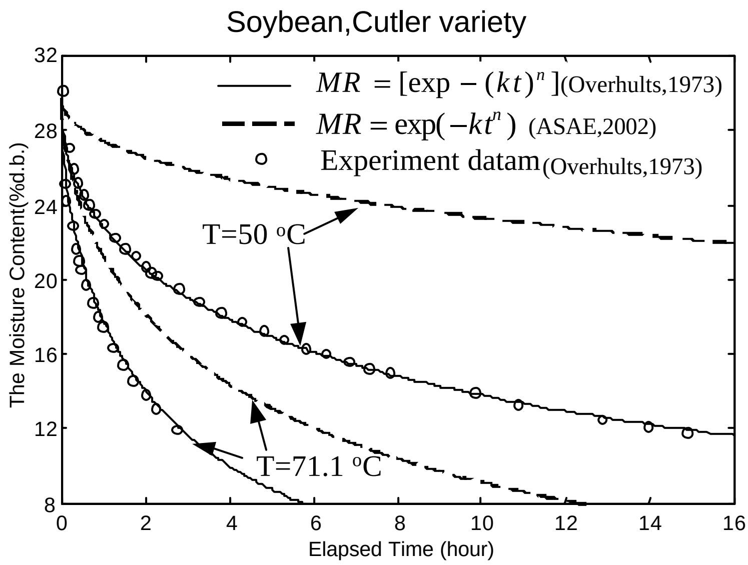

Figure 9 Predicted and experimental curves for soybean

Other similar situations concerning citing errors were also found in ASAE Standard-2001. One found in the citation of Rapeseed (Canola)[32], was the equation wrongly adopted as MR=exp$(-kt^n)$, in which k and n were the parameters instead of $MR = A\exp(-Bt)$ where A and B were the parameters.

Kulasiri et. al.[24] determined the thin-layer drying characteristics of Virginia-type peanuts, and obtained parameters for Page's two parameters model as below:

$$k=\exp(-0.780523-0.144026\,T_{db}+0.00358\,T_{db}^{2}+2.13914\,rh+0.715991\,Mi-0.13713\,T_{db}\,rh) \quad (30)$$

$$n=0.98867-0.019836\,T_{db}-0.000608\,T_{db}^{2}-1.033613\,rh-0.63824017\,Mi+0.0499769\,T_{db}\,rh \quad (31)$$

where $27.4°C \le T_{db} \le 35.5°C$, $0.226 \le rh \le 0.603$, $0.596 \le Mi \le 0.773$

The output of this model using the above parameters is shown in Figure 10, which is absolutely wrong for a thin-layer drying curve. This uncommon result implies the original source was incorrect. If we try to rearrange parameter n as:

$$n=-0.98867+0.019836T_{db}+0.000608T_{db}^{2}+1.033613\,rh+0.63824017Mi-0.0499769\,T_{db}\,rh \quad (32)$$

Where all the '+/–' signs were revised in reverse way, the predicted curve confirms to the data as shown in Figure 11. This fact suggested that in the original report of Kulasiri et. al. [24], the parameter n should be corrected to $-n$.

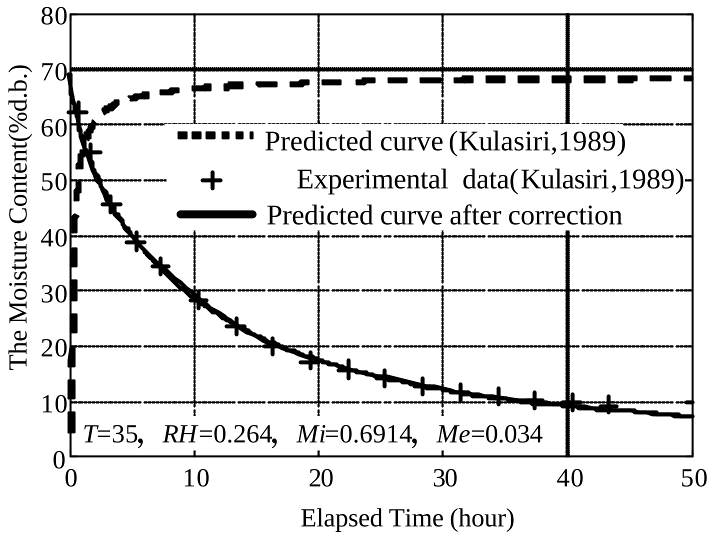

Figure 11 Predicted curve and experimental data for peanut

3.5 Deep Bed Drying

For a deep-bed drying, the drying air is moving vertically through the grain depth. A drying zone forms and passes through it slowly as the heat and mass exchanges between the grain and drying air.[13, 34] The logarithmic model was employed often by researchers.[6,14]

Simulation on the MATLAB will give us different views on the deep-bed drying process throughout the drying zone. Moisture content and temperature of grain at certain depth and drying time are becoming predictable to prevent deterioration of grain for a long period of drying.

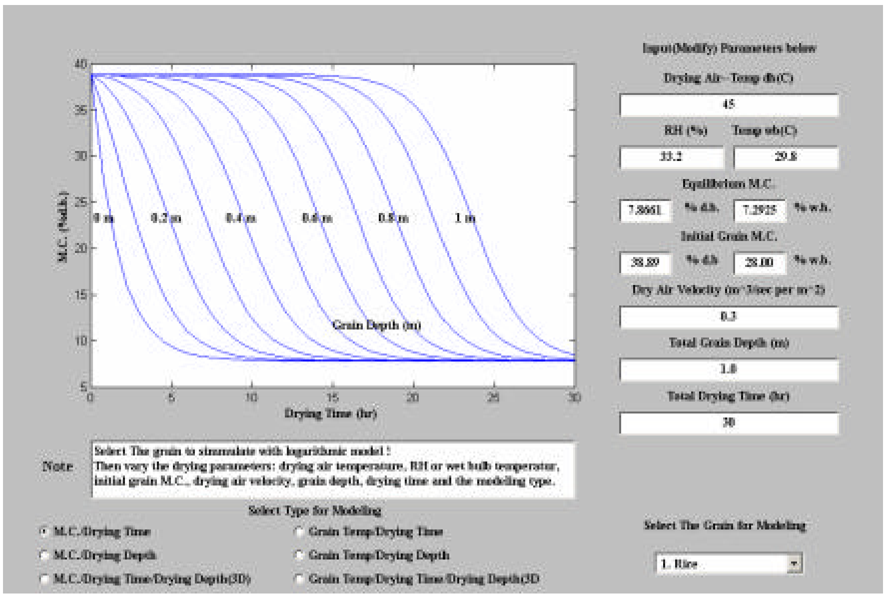

Figure 12 Moisture content vs drying time at certain grain depth

The simulation starts by selecting types of grain from pop-up menu, in which rice, shelled corn, soybeans, wheat, peanuts are included (Figure 12). The input parameters include air conditions like T_{db}, T_{wb}, rh, air flow rate and grain properties such as M_i, grain depth and drying time. The M_e of grain could be a direct input or derived from the air condition specified. The graphical output includes the changes of grain moisture or temperature with respect to drying time or grain depth. Both 2-D and 3-D plots are available as shown in Figures 12, 13.

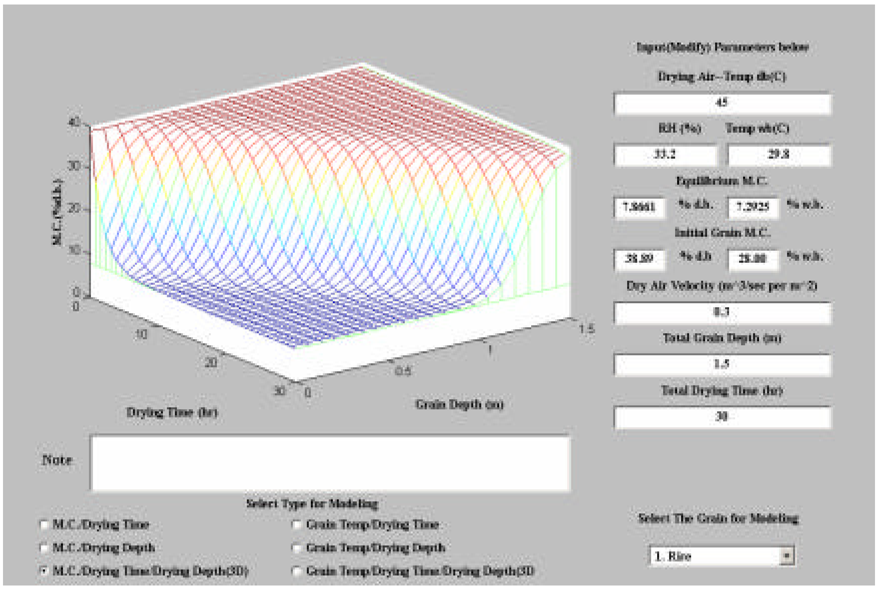

Figure 13 Moisture content vs. grain depth and drying time in 3-D.

4. CONCLUSION

With an easy-to-use environment, Matlab was applied to simulate the air and grain properties during drying process. This approach was proved to be successful especially in displaying the existing equations with a graphical mode. In virtue of its graphic user interface (GUI), the SAPGD-2004 software was developed to be an interactive and illustrative tool for simulating psychrometrics of moist air, resistance of grain to airflow (39 kinds of grain), equilibrium moisture content (45 grains, 97 sets of parameters), thin-layer drying curves (17 kinds of grain, 45 sets of equations) and deep-bed drying models (5 kinds of grain). Several errors were detected in thin-layer drying equations.

Researchers who are engaged in grain drying and storage studies will find it more convenient and efficient for information acquisitions. For students in-learning or teachers who are teaching the related courses, its build-in equations and parameters for various grains provide an illustrative and comprehensive environment. The SAPGD-2004 can also serve as a visualizing and handy tool for researchers to double check on the equations listed in the published literatures with the existing knowledge.

SAPGD-2004 software is free to the general public. All the required m files for the modules described in this paper is available by request via E-mail: dcwang@dlit.edu.tw.

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