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Circulating Concurrent-flow Drying Simulation of Rapeseed

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Abstract

In this study, computer simulations were conducted to assess the use of a circulating concurrent-flow dryer for rapeseed drying and to determined the effect of this drying method on the germination ratio of rapeseed after the drying process was complete. The simultaneous heat and mass transfer between air and rapeseed in a concurrent-flow dryer was examined by simulation. The drying simulation was based on several parameters with sequent time series. Equations concerning air psychrometrics, physical properties, thermal properties, equilibrium moisture content, thin layer drying of rapeseed, etc. were all combined to solve the simulation models. Based on energy and mass transfer in the concurrent-flow drying model, a simulation program for the circulating concurrent-flow rapeseed dryer was built along with a detailed description of the mathematical solution to the model.

A pilot scale circulating concurrent-flow dryer(200 kg/batch) was used to verify the fitness of the simulation program. A comparison between the experimental data and the model predicted results was presented and discussed. The drying parameters and germination ratio were analyzed and the accuracy of the simulation program was evaluated. The simulation program proved to be reliable and was shown to be a convenient tool for predicting rapeseed drying and germination ratio of rapeseed in a concurrent-flow dryer.

Keywords : Concurrent-flow, Drying model, Drying rate, Energy consumption, Germination ratio

1. INTRODUCTION

Rapeseed(Brassica napus L.) is normally harvested with a moisture content greater than 20%(w.b.), which results in high yields, and prevents field loss due to dropping and shattering. However, this moisture content is too high for safe storage and, thus, rapeseed must be dried to reach a safe moisture level for storage.

In recent years, the number of studies on the moving bed technique has significant increased, especially in regards to grain dryer applications. This technique requires a low investment, high drying rate, low energy consumption and causes less mechanical damage to the grain. The type of equipment used in any artificial drying process largely depends on mass and energy transfer between the drying air and the product. The drying process has been shown to be a function of eight variables: thickness of the grain bed, initial and final moisture content of the grain, grain temperature, bulk density, grain flow rate, inlet temperature and the humidity of air. Since this number of variables is more than can be handled empirically, simulations of grain drying have been developed to better understand and

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resolve issues associated with the drying process.

Mathematical modeling and computer simulations of grain drying are now widely used and have become an important tool for designing new driers and for analyzing existing drying systems. Mathematical modeling and computer simulations can be used to predict the moisture and temperature of the product during the drying process, and the energy consumption and drying capacity of the different drying systems. Many different models have been proposed to describe the drying process in basic types of convective grain dryers. Thompson et al.(1968) developed simulation models of a concurrent-flow dryer for corn drying. Felipe and Barrozo(2003) studied the simultaneous heat and mass transfer between air and soybean seeds in a concurrent moving bed dryer, which was based on using a two-phase model to simulate the drying process. In Korea, Han et al.(2006) studied a concurrent-flow for rice drying, where the drying temperature was varied from 98～126℃, and the air flow rate was varied from 28.5～57.1 cm/m^2. However, dynamic simulations of concurrent-flow for rapeseed drying have not yet been conducted.

The objective of this study was to simulate the rapeseed drying process in a circulating concurrent-flow dryer using mass and energy balance equations and a germination equation to predict the performance of the dryer and germination ratio of rapeseed, respectively, and to validate the simulation program.

2. MATERIAL AND METHODS

A. Mathematical model

Based on the theory of energy and mass transfer a concurrent-flow rapeseed drying model was developed. By using this mathematical models performance of concurrent-flow rapeseed dryer can be predicted, the temperature and moisture content of rapeseed, the temperature and relative humidity of drying air were predicted.

The thin layer drying models is used in simulation of deep-bed dryer, in which the average changes in moisture content and temperature on a thin layer of grain are calculated over a discrete time interval △t. In the simulation, to solve mathematical models of deep-bed drying process, the depth bed was divided into nth thin layers with thickness △x each and dynamic heat and mass balances were set up in each section (Fig. 1), and then the model consisted in a set of partial differential equations.

In order to develop these mathematical models, the following assumptions were made:

- No volume shrinkage occurs during the drying process.
- No temperature gradients exist within each grain particle.
- Particle-to-particle conduction is negligible.
- Airflow and grain flow are plug-type and constant.
- The dryer walls are adiabatic and no heat loss occurs.
- $\partial T/\partial t$ and $\partial H/\partial t$ are negligible compared to $\partial T/\partial x$ and $\partial H/\partial x$
- The heat capacities of moist air and grain are constant over short time periods.

Energy and mass balances were written on a differential volume located at an arbitrary location in the grain bed. There were four unknowns in this problem: the air temperature T(x, t), grain temperature q(x, t), the humidity ratio H(x, t), and the grain moisture content M(x, t).

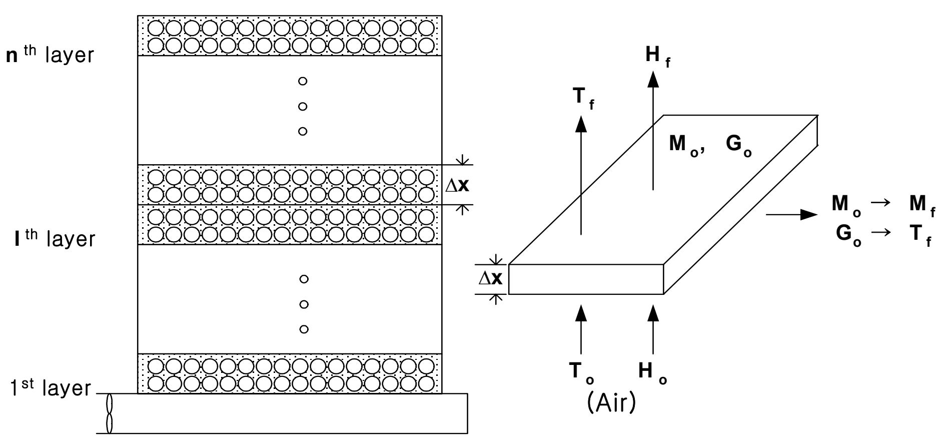


Fig. 1 Elemental of concurrent-flow drying.

Therefore, four equations must be balanced(Bakker et al., 1972; Keum, 1986). The four differential equations shown below(Equations (1)-(4)) constitute the concurrent-flow drying model.

$$\frac{dt}{dx}=\frac{-h_c a}{G_a c_a + G_a c_v H}(T-\theta) \tag{1}$$

$$\frac{d\theta}{dx}=\frac{h_c a}{G_p(c_p+Mc_w)}(T-\theta)-\frac{h_{fg}+c_v(T-\theta)}{G_p(c_p+Mc_w)}G_a\frac{dH}{dx} \tag{2}$$

$$\frac{dH}{dx}=-\frac{G_p}{G_a}\frac{dM}{dx} \tag{3}$$

$$\frac{dM}{dx}=\text{an appropriate thin layer drying equation} \tag{4}$$

where; a : specific surface area of grain(m^2/m^3)

c_a : specific heat of dry air(kJ/kgK)

c_p : specific heat of dry grain(kJ/kgK)

c_p : specific heat of water vapor(kJ/kgK)

c_w : specific heat of water in grain(kJ/kgK)

G_a : air flow rate(kg/hm^2)

G_p : grain flow rate(kg/hm^2)

h_{fg} : vaporization latent heat of water within grain(kJ/kg)

H : enthalpy of dry air(kJ/kg)

h_c : convection heat transfer coefficient(kJ/h m^2 ℃)

v_p : grain velocity(m/h)

To solve these differential equations(Equations (1)-(4)), the initial and boundary conditions of the rapeseed and the drying air must be known and furnished to the simulation program as input data. These initial and boundary conditions include the following: the initial or inlet temperature and moisture content of the grain, and the initial or inlet temperature and absolute humidity of the drying air. The specific initial and boundary conditions were:

$$T_{x=0}T_{in} \tag{5}$$

$$\theta_{x=0}=\theta_o \tag{6}$$

$$H_{x=0}=H_{in} \tag{7}$$

$$M_{x=0}=M_o \tag{8}$$

Related equations for the simulation were described in our previously published study, such as physical properties of rapeseed(Duc et al., 2008; Hong et al., 2009), equilibrium moisture content(Kim et al, 2008), thin layer drying equation (Duc et al., 2009) and germination properties of rapeseed (Duc and Han, 2009).

B. Numerical solution

In the numerical analysis, the Runge-Kutta methods, also referred to as RK4, were used. The general form of the RK4 method for this problem is given by the following equations(Fausett, 1999):

$$y_{n+1}=y_n+\frac{1}{6}(k_1+2k_2+2k_3+k_4) \tag{9}$$

where;
$$k_1=h\cdot f\left(y_n+\frac{k_1}{2},t_n+\frac{h}{2}\right) \tag{10}$$

$$k_2=h\cdot f\left(y_n+\frac{k_2}{2},t_n+\frac{h}{2}\right) \tag{11}$$

$$k_3=h\cdot f\left(y_n+\frac{k_2}{2},t_n+\frac{h}{2}\right) \tag{12}$$

$$k_4=h\cdot f(y_n+k_3,t_n+h) \tag{13}$$

To solve the mathematical models of the drying process, the depth bed was divided into ten thin layers, and dynamic heat and mass balances were set up in each section and calculated over a discrete time interval, $\Delta t=0.01h$.

C. Germination model

The germination tests were conducted according to protocols described by the standard germination test(Association of Official Seed Analysis, 1993). Constructional details of the apparatus and method are given elsewhere(Duc and Han, 2009). Experimentally, the total germination percentage(g) is obtained by dividing the number of seeds germinated by the total number of seeds within each experimental unit.

$$g=\frac{\sum n}{N}\cdot 100\% \tag{14}$$

The germination ratio(G) was determines as equation (15).

$$G=\frac{g}{g_i}\cdot 100\% \tag{15}$$

As discussed in our previous study(Duc and Han, 2009), equation (16) was used to describe the effect of drying conditions on the germination ratio of rapeseed. This model predicted the germination ratio with high accuracy and reliability.

$$G = 88.3917 + 0.784167 \times T - 26.7222 \times RH - 0.019 \times T^2 + 0.916667 \times T \times RH \quad (16)$$

D. Drying test of model validation

In order to verify the fitness of the simulation program, a pilot-scale concurrent-flow dryer was used. The principles of the concurrent-flow rapeseed dryer are shown in Fig. 1. The main structure of the dryer includes a grain inlet section, burner, plenum section, drying section, tempering section, suction centrifugal fan, variable speed discharge augers and bucket elevator. The dimension of drying chamber(height length width) is 0.5, 0.7, 0.5 m. Height of tempering section is 0.5 m.

During experiment the drying air temperature and grain temperature are continuously measured. For measurement temperature of drying air and rapeseed, 16 temperature sensors(T-type, Omega, USA) were installed inside the dryer. Data from sensors were transferred to Data logger(Datascan 7327, UK) and recorded by two computers. In plenum section, 3 sensors were installed to measure drying air temperature input. In exhaust air ducts, 4 sensors were installed(2 sensor at upper and 2 sensors at lower ducts) to measure exhaust air temperature. In drying chamber, 6 sensors were installed to measured rapeseed temperature. To measure rapeseed temperature after dying, 2 sensors were installed at above of two discharge augers. And one sensor was installed outside the dryer to measure ambient air temperature. Ambient air relative humidity and exhaust air relative humidity were recorded by hygrometer(MTH4100, Sanyo, UK).

Grain flow velocity was set up at 5 m/h, controlled by discharge augers, equivalent to the mass of circulated rapeseed is 1000 kg/h.

In order to suck the exhaust drying air, suction fan(Samwha, Korea) with air flow rate 30 cmm/m^2, 1 HP was used. Velocity of drying air was measured by anemometer (Velocicalc-Plus, TSI, USA).

The jet-burner(OL-3, Deawon, Korea) using Kerosene. This burner can be raise drying air temperature up to 140℃. To control the burner, temperature sensor(PT-100) was installed at the influx duct and temperature control equipment (HSD-V2, Hansung, Korea) was used. Electric balance(A-200, Cass, Korea) was use to weigh the mass of Kerosene loss by drying process.

Spring rapeseed samples, variety Sunmang F1-hybrid, were harvested in June in Jeonnam-do, Yeonggwang-gun. The samples cleaned and stored in refrigerator at a temperature of 4℃(Cassells et al., 2003). 200 kg of rapeseed with average initial moisture content is 23.0%(w.b.) and 23.2% (w.b.) was used in Test-1 and Test-2, respectively.

The average temperature of drying air in plenum chamber during drying process is 89.4℃ and 116.8℃ for Test-1 and Test-2, respectively. Detailed drying conditions in for Test-1 and Test-2 shown in table 6-4 and results of rapeseed drying in pilot-scale dryer were summarized in table 1.

Table 1 Initial rapeseed and drying conditions for drying tests

Conditions	Test-1	Test-2
Initial weight(kg)	200	200
Initial moisture content(%,w.b.)	23.0	23.2
Initial grain temperature(℃)	22.8	24.7
Initial germination rate(%)	98.5	97.7
Drying temperature(℃)	89.4	116.8
Airflow rate(cmm/m^2)	30	25
Ambient temperature(℃)	25.4	28.6
Ambient relative humidity(%)	71.6	63.4

The simulation program was validated by comparing the results of the program with experimental data obtained from a pilot scale concurrent-flow dryer as described. The input data for the simulation program were entered in accordance with data obtained from the actual experiment, such as initial rapeseed conditions, dryer specification, and drying air and ambient air conditions. The fitness of the simulated results with the experimental results was evaluated based on the coefficient of determination(R2) and the root mean square error(RMSE).

3. RESULTS AND DISCUSSION

A. Simulation program

MATLAB is an interactive program that can be used to conduct numeric computations and data visualization(Chapre, 2005). The numerical solution for four ordinary differential equations was obtained using a MATLAB program(MATLAB 7.3.0, R2006b version) based on fourth-order Runge-Kutta

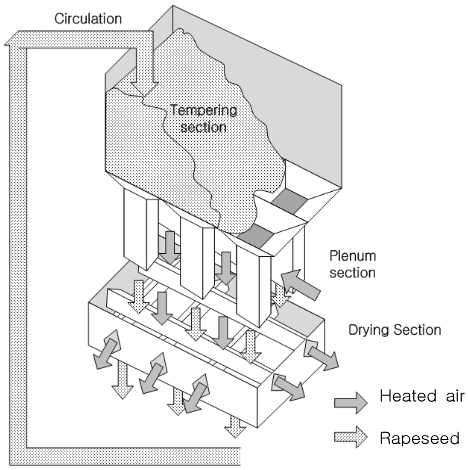


Fig. 2 Schematic diagram of the pilot concurrent-flow dryer.

methods. The concurrent-flow dryer simulation model was programmed with the following sequence: Input data; Initialize arrays; Evaluate constants; Solve four ordinary differential equations; Output when appropriate. Equations used by more than one model(e.g. psychrometric equations) were programmed as separate subroutines of the function subprogram.

B. Model validation

The temperature of the rapeseed was also analyzed and evaluated. In Test-1, the $R^2$and RMSE of the moisture content versus drying time were 0.994 and 0.334%(w.b.), respectively. In Test-2, the R^2 and RMSE of the moisture content were 0.997 and 0.506%(w.b.), respectively. A comparison between the experimental and predicted moisture content for Test-1 and Test-2 is shown in Fig. 3a&b.

Based on the analytical results, a good fitness between the predicted moisture content and the experimentally measured moisture content was observed for both Test-1 and Test-2. The moisture content determined by simulation versus the measured values are presented in Fig. 4, where the data points are clearly distributed close to the perfect fit line(measured values = predicted values). This result clearly demonstrated that this novel simulation program for predicting the moisture content of rapeseed in a concurrent-flow dryer was highly accurate.

The predicted temperature of rapeseed during the drying process strongly correlated with the experimental data. The R^2 and RMSE of the rapeseed temperature were 0.904 and 1.15℃ in Test-1, and 0.925 and 1.77℃ in Test-2, respectively. A comparison between the experimental and predicted temperature of rapeseed during the drying process is shown in Fig. 5a&b.

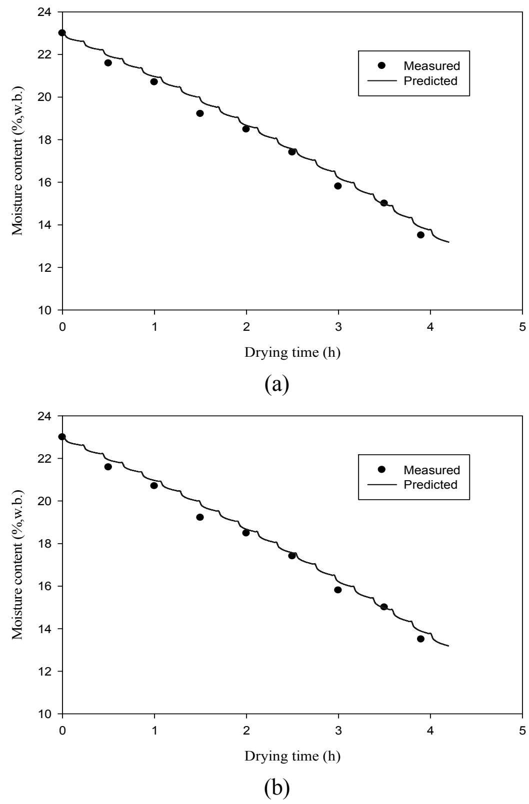


Fig. 3 Comparison of the experimental and predicted moisture content in (a) Test-1, and (b) Test-2.

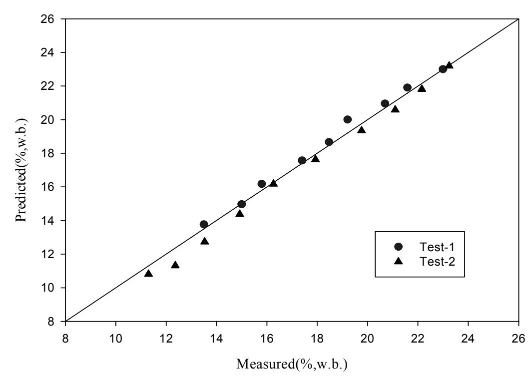
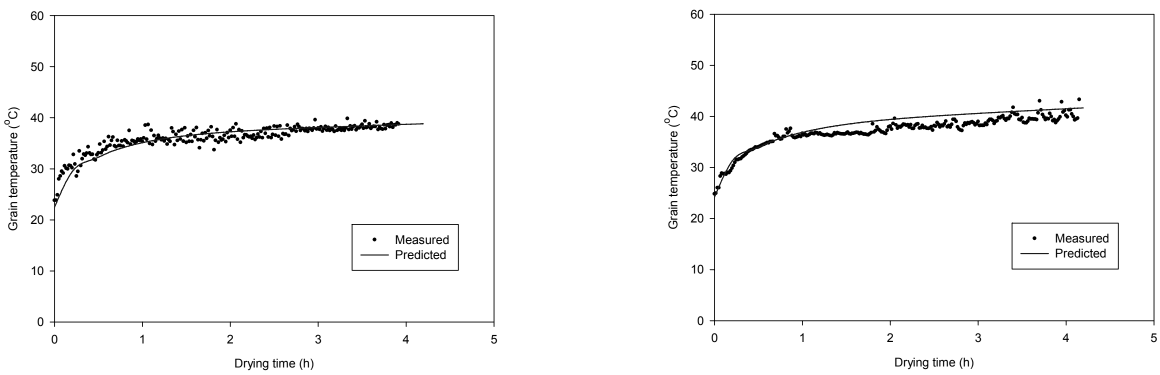


Fig. 4 Experimentally measured moisture content versus predicted moisture content.

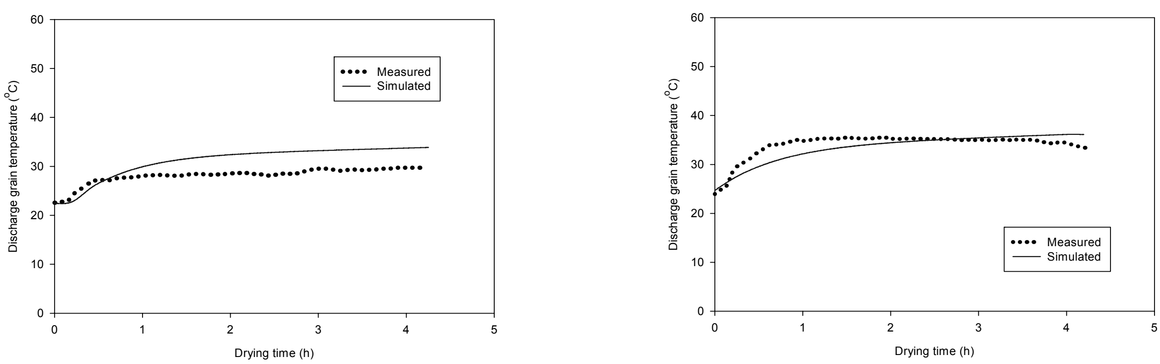
The R^2 and RMSE of the temperature of discharged rapeseed were 0.940 and 3.56℃ in Test-1, and 0.846 and 1.40℃ in Test-2, respectively. A comparison between the experimental and predicted temperature of discharged rapeseed is shown in Fig. 6a&b.

The difference between the experimental and predicted temperature of rapeseed during the drying process in both



(a) (b)

Fig. 5 Comparison of the experimental and predicted temperature of rapeseed during the drying process in a) Test-1, and b) Test-2.



(a) (b)

Fig. 6 Comparison of the experimental and predicted temperature of discharged rapeseed in a) Test-1, and b) Test-2.

Test-1 and Test-2 was very small. Based on these analytical results, the predicted values were found to have a good fitness to the experimental values.

The predicted discharged rapeseed temperature tended to be higher than the experimentally determined temperature during the drying process. It was possible that in the discharged rapeseed temperature measurements additional heat losses occurred because of heat transfer from the dryer wall during the transport of the seed, which was neglected in the model. This would cause a decrease in the real experimental value of this variable. Particularly when the drying air temperature is very high, as was the case in Test-2. In this scenario, the temperature of the discharged rapeseed at the beginning of the drying process was higher than the predicted value, which may be due to the fact that particle-to-particle conduction was ignored as well as the existence of temperature gradients within each grain particle. Therefore, the differences between the simulation model and experimental values are most likely due to the model assumptions. Despite this, the average differences between the experimental and predicted data were small and there was a good fitness between the model values and the experimentally determined values.

The final moisture content, drying rate, fuel energy consumption and germination ratio were investigated. The measured germination ratio in Test-1 and Test-2 were 94.7% and 84.5%, respectively. The experimental and predicted results of Test-1 and Test-2 are listed in table 2.

The difference between the predicted value and measured value for the drying rate were 5.0% and 5.4%. The predicted values of the germination ratio after drying were 1.9% and 9.5% higher than the measured values for Test-1 and Test-2, respectively. These differences might have originated from sequential changes in hot air temperature, ambient temperature, and humidity in the simulation model and experimental conditions. Besides, the dryer wall effect on the bed porosity, which was neglected in the model, also affects the predicted results. The higher value of the bed porosity near the dryer wall can change the air velocity profile, increasing the air velocity in regions close to the dryer wall and decreasing it in the central bed region.

Table 2 Comparison of the experimental and predicted results of Test-1 and Test-2

Output	Test-1			Test-2		
	Measured	Predicted	Difference (%)	Measured	Predicted	Difference (%)
Final moisture content (%,w.b.)	13.8	13.5	2.2	11.4	10.8	5.3
Drying rate (%,w.b./h)	2.38	2.26	5.0	2.80	2.95	5.4
Fuel energy (kJ/kg-water)	4915	5153	4.8	4831	4417	8.6
Germination ratio(%)	94.7	96.5	1.9	84.5	92.5	9.5

4. CONCLUSIONS

The combined theoretical and experimental studies were carried out to gain a better and more comprehensive understanding of the behavior of rapeseed drying. Based on energy and mass transfer of the concurrent-flow drying model, a simulation program for a circulating concurrent-flow rapeseed dryer was built. The fouth-order Runge-Kutta method was used to solve the four ordinary differential equations of the concurrent-flow drying model. A pilot scale concurrent-flow dryer(200 kg/batch) was used to validate the fitness of the simulation program. Two drying experiments were conducted. Data on temperature and moisture content were collected and energy consumption and germination ratio were experimentally calculated.

Based on the analytic results, a good fitness between the simulation program and the experimental data was observed. The RMSE of the predicted moisture content ranged from 0.334 to 0.506%(w.b.) and the coefficient of determinations ranged from 0.994 to 0.997. The RMSE of the predicted rapeseed temperature during the drying process ranged from 1.15 to 1.77℃ and the coefficient of determinations ranged from 0.904 to 0.925. The experimental drying rates were 2.38%,w.b./h in Test-1, and 2.80%,w.b./h in Test-2. In comparison to the predicted values, the difference between the predicted value and measured value for the drying rate was 5.0% and 5.4%. The predicted values of the germination ratio after drying were 1.9% and 9.5% higher than the measured values. The simulation program proved to be reliable and was shown to be a convenient tool for predicting rapeseed drying and germination ratio of rapeseed after drying in a concurrent-flow dryer.

REFERENCES

1. American Society of Agricultural Engineers S352.2. 2004. Moisture measurement-Unground grain and seeds. ASAE standards 51st Edition 582-583.
2. Association of Official Seed Analysis. 1993. Rules for testing seeds. Journal of Seed Technology 16:1-113.
3. Bakker-Arkema, F. W., D. B. Brooker and C. W. Hall. 1972. Comparative evaluation of cross-flow and concurrent flow grain dryers. ASAE Paper No 72-849.
4. Cassells, J. A., L. P. Caddick., J. R. Green and R. Reuss. 2003. Isotherms for Australian canola varieties. Proceedings of the Australian Postharvest Technical Conference 59-63.
5. Chapre, S. C. 2005. Applied numerical methods with Matlab for engineers and scientists. McGraw-Hill International Inc., NewYork.
6. Duc, L. A., D. H. Keum and J. W. Han. 2009. The thin layer drying characteristics of rapeseed(Brassica napus L.). Accepted for publishing by Journal of Stored Products Research Paper No. SPR-D-08-00101.
7. Duc, L. A., J. W. Han., S. J. Hong., H. S. Choi., Y. H. Kim and D. H. Keum. 2008. Physical properties of rapeseed (I). Journal of Biosystems Engineering 33(2):101-105. (In Korean)
8. Duc, L. A and J. W. Han. 2009. The effects of drying conditions on the germination properties of rapeseed. Journal of Biosystems Engineering 34(1):30-36.
9. Fausett, L. V. 1999. Applied numerical analysis using Matlab. Prentice Hall Inc., Upper Saddle River, New Jersey 07458.
10. Felipe, C. A. S. and M. A. S. Barrozo. 2003. Drying of soybean seeds in a concurrent moving bed: heat and mass transfer and quality analysis. Drying Technology 21(3):439-456.
11. Han, J. W., D. H. Keum., J. G. Han., H. Kim and S. J. Hong. 2006. Development of rice circulating concurrent-flow dryer (I) - Performance test of pilot scale dryer. Korean Society for Agricultural Machinery 31(4):349-354. (In Korean)
12. Hong, S. J., L. A. Duc., J. W. Han., H. Kim., Y. H. Kim and D. H. Keum. 2008. Physical properties of rapeseed (II). Journal of Biosystems Engineering 33(3):173-178. (In Korean)
13. Keum, D. H. 1986. Data and equations for the analysis of rough rice drying. Korean Society for Agricultural Machinery 11(2):92-102. (In Korean)
14. Kim, Y. H., J. W. Han and D. H. Keum. 2008. Desorption EMC Models for Rapeseed. Journal of Biosystems Engineering 32(6):403-407. (In Korean)
15. Thompson, T. L., R. M. Peart and G. H. Foster. 1968. Mathematical simulation of corn drying - a new model. Transactions of the ASAE 24(3):582-586.