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Chapter

# Mathematical Modeling and Simulation of Rapeseed Drying on Concurrent-Flow Dryer

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## Abstract

Mathematical modeling for rapeseed drying on concurrent-flow dryer was built based on energy and mass transfer balances. The fourth-order Runge–Kutta method was used for solving four ordinary differential equations. A computer simulation program for circulating concurrent-flow rapeseed dryer was developed using these models. A pilot-scale concurrent-flow dryer was used to verify the fitness of simulation program. Two drying experiments were conducted. The output parameters of the simulation program were compared and analyzed with experiment data. The RMSE of simulated moisture contents ranged from 0.334 to 0.506% w.b. with the coefficient of determinations ranged from 0.994 to 0.997. The RMSE of simulated rapeseed temperatures during drying process ranged from 1.15 to 1.77°C with the R<sup>2</sup> ranging from 0.904 to 0.925. The experimental drying rates were 2.38 and 2.80% w. b./h. In comparison with simulated values, the difference between simulated value and measured value of drying rate were 5.04 and 5.08%; drying time were 7.14 and 0.47%; and germination ratio were 1.87 and 0.47%. The simulated fuel energy consumption for drying were 4.62 and 8.57% lower than the experimental values. The analytic results showed that the simulation results have good fitness with experimental data.

**Keywords:** concurrent-flow dryer, mathematical modeling, simulation, drying rate, grain temperature, moisture content

## 1. Introduction

There are many different grain dryer designs on the market. Basically, the classical configurations of the moving bed dryers fall into four categories according to the relative directions of seed and air flows: the mixed flow dryer, the cross flow dryer, the concurrent-flow dryer, and the countercurrent flow dryer. The configuration with parallel concurrent-flow displays some advantages, such as obtaining of more homogeneous products as well as a better energy usage.

Concurrent-flow drying is a relatively new grain drying technology. In a concurrent-flow dryer, both the grain and drying air are moving in the same direction. This type of dryer has the advantage of using very high drying air temperatures without affecting grain quality and does not suffer the variation in grain moisture contents. Besides, energy efficiency of this type dryer is high.

The concurrent-flow drying principle was introduced the first time in 1955 by Öholm. Thompson et al. [1] developed simulation models of concurrent-flow dryer for corn drying. Now most of the drying simulation model was implemented based on the model presented by Thompson et al. that was developed for simulating high temperature corn drying. Felipe and Barrozo [2] studied the simultaneous heat and mass transfer between air and soybean seeds in a concurrent moving bed dryer, based on the application of a two-phase model to the drying process. Keum et al. [3] studied on circulating concurrent flow for rice drying with the drying temperature from 98 to 126°C, and air flow rate from 28.5 to 57.1 cmm/m<sup>2</sup>. The study results showed that drying rate ranged from 1.09 to 2.2% d.b./h, and energy consumption ranged from 6224 to 6992 kJ/kg-water.

From these advantages, the use of concurrent-flow drying principle for drying of rapeseed has been recommended owing to:

- Energy saving: energy efficiency of this type dryer is about 30–40% better than a cross flow type dryer without heat recovery.
- It is possible to use a high drying temperature (up to 130°C) without increasing the grain temperature excessively because grain are exposed to drying air in a short time, leads to high drying rate (1.5–2% w.b./h).
- The drying air flow is parallel to the grain flow leads to more homogeneous moisture content and temperature distributions because all grains are exposed to the same temperatures, therefore guaranteeing the quality of the dried grains.

Mathematical modeling and computer simulation can be used to predict the moisture and temperature of the products during the drying process and the energy consumption and drying capacity of the different drying system. Many different models have been proposed to describe the drying process in the basic types of convective grain dryer. However, no previous research was found in literature that study on dynamic simulation of concurrent flow for rapeseed.

## 2. Concurrent-flow drying model

## 2.1 Selection of drying principle

The drying process of rapeseed in concurrent-flow dryer was described in **Figure 1**.

The hot air and rapeseed are moving the same direction in the drying chamber. At the end of cycle drying, hot air is exhausted to ambience by suction fan; rapeseed is continued to be circulated on the drying chamber for the next cycle drying until it reaches the desired final moisture content.

## 2.2 Mathematical model

The mathematical model used in the study consists of a set of four partial differential equations in four independent variables: air humidity, air temperature, grain temperature, and grain moisture content.

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



**Figure 1.** Block diagram of rapeseed concurrent-flow dryer.



**Figure 2.** *Concurrent-flow drying model.* 

content of rapeseed and 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  $\Delta t$ . In the simulation, to solve mathematical models of deep-bed drying process, the depth bed was divided into nth thin layers with a thickness of  $\Delta x$  each, and dynamic heat and mass balances were set up in each section, and then the model consisted in a set of partial differential equations (**Figure 2**). Drying is achieved by continuously passing hot air through the static grain bed in one direction, from the top to the bottom section. From the first thin layer at the top section, the air evaporates moisture from the grain and carries it to the next thin layer. As the drying air absorbs moisture, its temperature is decreased, and its ability to pick up more moisture (drying potential) decreases. A deep bed consisting of a number of thin layers is, therefore, simulated by calculating the air and moisture changes as the drying air passes from one thin layer of grain to the next layer. Each layer dries to equilibrium conditions for short time intervals, and the exhaust air from one layer is used as the input drying air to the next. The drying procedure continues for a number of drying time intervals until the desired final moisture content of the material is achieved.

Some of these assumptions are made to simplify the mathematical model. So, for developing these mathematical models, the following assumptions were made:

- Operation is in the steady state.
- Grain shrinkage is negligible during the drying process.
- No temperature gradients exist within each grain particle.
- Particle-to-particle conduction is negligible.
- Initial moisture content of grain is uniform.
- Airflow and grain flow are plug-type and constant.
- The dryer walls are adiabatic and heat losses are negligible.
- The heat capacities of moist air and of grain are constant during the short time periods.
- The solids flow rate is uniform.

Energy balances and mass balances are written on a differential volume  $(S \cdot \Delta x)$  located at an arbitrary location in the grain bed. There are four unknowns in this problem:

T(x,t): the air temperature.

 $\theta(x,t)$ : the grain temperature.

H(x,t): the humidity ratio.

M(x,t): the grain moisture content.

Therefore, four equations for material and energy balances must be made in order to calculate of T,  $\theta$ , H, and M. Resulting from the balances are four Eq. (4):

1. For the enthalpy of the air (air enthalpy balance):

The change in sensible heat of air that results due to heat transfer by convection in time. The air enthalpy balance over the differential volume:

energy out = energy in – energy transferred by convection  

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

2. For the enthalpy of the grain (grain enthalpy balance):

The enthalpy from the air to the grains due to convection heat transfer over the control volume is equal to the required heat to evaporate water inside the grains and to heat water vapor extracted from the grains and the rate of accumulated heat inside the grains. The grain enthalpy balance over the differential volume:

energy transferred = change in internal grain energy - energy for evaporation

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

3. For the humidity of the air (humidity balance):

The amount of water in and out the differential volume is equal to the rate of change of moisture content in the grains.

moisture transferred = moisture in-moisture out

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

4. For the moisture content of the grain (thin layer drying equation):

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

$$\frac{dM}{dx} = \frac{M_o - M_e}{v_p} \left(-Pt^{Q-1}Q\right) \exp\left(-Pt^Q\right)$$
(4)

where:

a: specific surface area of grain  $(m^2/m^3)$ .  $c_a$ : specific heat of dry air  $(kJ/kg\cdot K)$ .  $c_p$ : specific heat of dry grain  $(kJ/kg\cdot K)$ .  $c_v$ : specific heat of water vapor  $(kJ/kg\cdot K)$ .  $c_w$ : specific heat of water in grain  $(kJ/kg\cdot K)$ .  $G_a$ : air flow rate  $(kg/h\cdot m^2)$ .  $G_p$ : grain flow rate  $(kg/h\cdot m^2)$ .  $h_{fg}$ : vaporization latent heat of water within grain (kJ/kg). H: enthalpy of dry air (kJ/kg).  $h_c$ : convection heat transfer coefficient  $(kJ/h\cdot m^2\cdot C)$ .  $v_p$ : grain velocity (m/h).

Eqs. (1) and (2) represent the respective energy balances. Eqs. (3) and (4) result from mass balances applied for both fluid and solid phases of a concurrent-flow dryer.

The equation for the moisture content is obtained from the empirical thin layer equation for rapeseed. The four differential equations from (1)–(4) constitute the concurrent-flow drying model. A computer simulation program was developed using these models.

To solve these differential equations, the initial and boundary condition of grain and the drying air must be known and furnished to the simulation program as input data [4]. In this category fall:

- The initial or inlet temperature and moisture content of grain
- The initial or inlet temperature and absolute humidity of the drying air

The initial conditions of the air humidity, grain moisture, and both air and grains temperatures were assumed constant at the dryer inlet, resulting in the following model boundary conditions (x = 0) for concurrent-flow dryer which are:

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

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

$$\mathbf{H}_{\mathbf{x}=\mathbf{0}} = \mathbf{H}_{\mathrm{in}} \tag{7}$$

$$\mathbf{M}_{\mathbf{x}=\mathbf{0}} = \mathbf{M}_{\mathbf{0}} \tag{8}$$

where:  $T_{in}$ : inlet air temperature (°C).  $\theta_o$ : initial grain temperature (°C).  $H_{in}$ : inlet humidity ratio of drying air (kg/kg).  $M_o$ : initial moisture content of grain (dec., d.b.)

#### 2.3 Related equations

The related equations used for simulation such as specific surface area, latent heat, convection heat transfer coefficient, equilibrium moisture content, and thin layer drying equation of rapeseed were taken from specific studies.

#### 2.3.1 Specific surface area of rapeseed

Specific surface area of rapeseed was determined in Eq. (9) [5]:

$$a = \frac{6(1-\varepsilon)}{d} \tag{9}$$

where:

 $\varepsilon$ : void fraction was calculated based on bulk density and true density of rapeseed,  $\varepsilon$  = 0.389.

d: diameter of rapeseed was determined in our previous study, d =  $2.21 \times 10^{-3}$  m [6]. Then, the specific surface area of rapeseed is a =  $1659 \text{ m}^2/\text{m}^3$ .

#### 2.3.2 Latent heat

Gallaher [7] established the following equation Eq. (10) to determine the dependence of the latent heat of vaporization of water from the product on its moisture content:

$$h_{fg} = h_{fgo} \cdot [1 + A \cdot \exp((-B \cdot M))]$$
(10)

 $h_{fg}$ : latent heat of vaporization of water in grain (kJ/kg-water).  $h_{fgo}$ : latent heat of vaporization of free water (kJ/kg-water).

 $h_{fgo} = (2502.2 - 2.386 \cdot T)$ 

T: drying air temperature (°C).

M: rapeseed moisture content (decimal, d.b.)

A, B: coefficients.

The coefficients A and B were determined based on equilibrium moisture content of rapeseed (Modified Halsey equation) [8].

The values of the relative humidity can be replaced by equilibrium relative humidity (ERH) obtained from the equilibrium moisture content versus ERH relationships described in above section. Then:

$$P_{v} = P_{s} \bullet ERH \tag{11}$$

The relationship between vapor pressure and latent heats of two substances at the same temperature is as follows [5]:

$$\ln P_v = \frac{h_{fg}}{h_{fgo}} \ln P_s + C \tag{12}$$

where C is a constant of integration.

The ratio of heat of vaporization of water in grain to the heat of vaporization of saturated water on a logarithmic scale gives the ratio of latent heat  $h_{fg}/h_{fgo}$  at each level of moisture content as the slope of the straight line obtained from Eq. (12):

 $\frac{h_{fg}}{h_{fgo}} = 1 + A \cdot \exp(-B \cdot M)$ (13)

Using MATLAB simulation program, the coefficients were found. A = 0.3734.

B = 14.2442.

This result is fairly similar to the result of Cenkowski et al. [9]: A = 0.5; B = 14.5. Convection heat transfer coefficient [5]:

$$h_c = 0.277 \cdot G_a \cdot \left(\frac{d \cdot G_a}{\mu_a}\right) \tag{14}$$

where:

h<sub>c</sub>: convection heat transfer coefficient of grain bed (kJ/h·m<sup>2</sup>·K). d: geometric mean diameter of rapeseed (m).  $\mu_a$ : dynamic viscosity of air (kg/h·m).

$$\mu_a = 0.06175 + 0.000165 \cdot T \tag{15}$$

(17)

T: drying temperature (K).

Equilibrium moisture content [8]:

Equilibrium moisture content of rapeseed was determined using Modified Halsey equation:

$$M = \left[\exp\left(-4.9758 - 0.0132 \cdot T\right)\right]^{1/1.8755} \left(-\ln RH\right)^{-1/1.8755}$$
(16)

Thin layer drying [10]:

Thin layer drying equation of rapeseed was determined using model of Page:

$$\mathrm{MR} = \exp\left(-P \cdot t^{Q}\right)$$

where the drying constants were determined: P =  $0.02246 + 3.2428 \cdot RH + 0.0006308 \cdot T^2 - 2.01481 \cdot RH^2 - 0.06077 \cdot T \cdot RH$ . Q =  $0.60932 - 1.72018 \cdot RH^2 + 0.02529 \cdot T \cdot RH$ .

#### 2.4 Numerical solution

Eqs. (1)-(4) and the boundary conditions Eqs. (5)-(8) were solved using the Runge-Kutta methods.

In numerical analysis, the Runge–Kutta methods are an important family of iterative methods for the approximation of solutions of ordinary differential equations (ODEs). These techniques were developed around 1900 by the German mathematicians Runge C. and Kutta M.W. One member of the family of Runge–Kutta methods that is so commonly used is the fourth-order Runge–Kutta method or also called as RK4, meaning that the error per step is on the order of  $h^5$ , while the total accumulated error has order  $h^4$  [11].

Let an initial value problem be specified as follows:

$$y' = f(y, t), y(t_0) = y_0$$
 (18)

where f(t,y) is a function of y and t and the second equation is an initial condition.

In order to calculate  $y_{n+1}$  with a known value of  $y_n$ , integrate Eq. (18) in the interval  $t_n \ge t \ge t_{n+1}$  to yield.  $y_{n+1} = y_n + \int_{t_n}^{t_{n+1}} f(y,t) dt$ (19)

The RK4 method is derived by applying a numerical integration method to the right side of Eq. (19). Then, the general form of the RK4 method for this problem is given by the following equations:

$$y_{n+1} = y_n + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4)$$
(20)

$$t_{n+1} = t_n + h \tag{21}$$

for n = 0, 1, 2, 3, ...

$$k_1 = h f(y_n, t_n) \tag{22}$$

$$k_2 = h.f\left(y_n + \frac{k_1}{2}, t_n + \frac{h}{2}\right)$$
(23)

$$k_{3} = h f\left(y_{n} + \frac{k_{2}}{2}, t_{n} + \frac{h}{2}\right)$$
(24)

$$k_4 = h f \left( y_n + k_3, t_n + h \right) \tag{25}$$

h: size of the interval

Thus, the next value  $(y_{n+1})$  is determined by the present value  $(y_n)$ . The slope is a weighted average of slopes:

 $k_1$  is the slope at the beginning of the interval.

 $k_2$  is the slope at the midpoint of the interval, using slope  $k_1$  to determine the value of y at the point ( $t_n + h/2$ ) using Euler's method.

 $k_3$  is again the slope at the midpoint, but now using the slope  $k_2$  to determine the y-value.

 $k_4$  is the slope at the end of the interval, with its y-value determined using  $k_3$ .

In averaging the four slopes, greater weight is given to the slopes at the midpoint:

$$slope = \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4) \tag{26}$$

To solve mathematical models of drying process, the depth bed model was divided into 10 thin layers, and the dynamic heat and mass balances were set up in each section and calculated over a discrete time interval  $\Delta t = 0.01$  h.

## 3. Simulation program

### 3.1 Main program

The numerical solution for four ordinary differential equations was obtained by using MATLAB code programs based on fourth-order Runge–Kutta methods. MATLAB 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. MATLAB-based software, entitled RCDSim-LAD (Rapeseed Concurrent-flow Drying Simulation, version LAD), was built for drying simulation. The concurrent-flow dryer simulation model was programmed with the sequence:

- Input data
- Initialize arrays
- Evaluate constants
- Solve four ordinary differential equations
- Output when appropriate

The program of concurrent model terminates in one of two ways:

- When the moisture content within the dryer reaches a specified level
- When condensation or absorption is detected

However, condensation or absorption is not simulated in the concurrent model since it does not occur in a properly designed dryer. Equations used by more than one model (e.g., psychrometric equations) are programmed as separate subroutines of function subprogram. A computer simulation program was built using these models. This program was used in predicting the performance and temperature profile within the grain bed.

Input data	Output data
Initial grain condition:	Drying time (h)
• Initial grain moisture content (dec, w.b.)	Number of pass
• Initial grain temperature (°C)	Final moisture content (% w.b.)
• Desired final moisture content (dec,w.b.)	Drying rate (% w.b./h)
Dryer specification:	Water removal rate (kg/m <sup>2</sup> )
• Capacity (kg)	Fan static pressure (Pa)
• Drying air flow rate (cmm/m <sup>2</sup> )	Fan power (kW/m <sup>2</sup> )
Grain flow velocity (m/h)	Fan energy (kJ/kg-water)
Drying and ambient air condition:	Fuel energy (kJ/kg-water)
• Drying air temperature (°C)	Total energy consumption (kJ/kg-water)
• Ambient air temperature (°C)	
• Ambient air relative humidity (dec.)	

#### Table 1.

Input and output data in the simulation program.

**Table 1** listed input data and output data which was simulated by a simulation program. The flow chart of the simulation program is shown in **Figure 3**. For the convenience, the interface graphical user interface (GUI) was built in **Figure 4**.

#### 3.2 Energy consumption

#### 3.2.1 Fuel energy consumption

$$EnFuel = \frac{G_a \cdot (c_a + c_v \cdot h) \cdot (T - T_{amb}) \cdot t}{0.85 \cdot (M_o - M_f) \cdot \rho_g \cdot x}$$
(27)  
where:  
EnFuel: fuel energy consumption (kJ/kg-water).  
G\_a: air flow rate (kg/h·m<sup>2</sup>).  
c\_a: specific heat of dry air (kJ/kg·K).  
c\_v: specific heat of water vapor (kJ/kg·K).  
h: absolute humidity (kg-water/kg-dry air).  
T: drying air temperature (°C).  
T\_{amb}: ambient air temperature (°C).  
t: drying time (h).  
 $M_o$ : initial moisture content (decimal, d.b.)  
 $M_f$ : final moisture content (decimal, d.b.)  
 $\rho_g$ : dry grain bulk density (kg/m<sup>3</sup>).  
x: grain layer thickness (m).

3.2.2 Fan power

$$PFan = \frac{\Delta P \cdot g_a \cdot A}{60 \cdot e_f \cdot 1000} \tag{28}$$

where: PFan: fan power (kW).  $\Delta P$ : pressure drop (Pa). A: cross-section area of grain bed (m<sup>2</sup>).  $g_a$ : air flow rate (m<sup>3</sup>/min·m<sup>2</sup>).  $e_f$ : efficiency of the fan and motor (usually a value of about 0.5 is used).

3.2.3 Fan energy consumption

$$EnFan = \frac{PFan \cdot t \cdot 3600}{(M_o - M_f) \cdot \rho_g \cdot x}$$
(29)

where:

EnFan: fan energy consumption (kJ/kg-water).

3.2.4 Total energy consumption

$$EnTot = EnFuel + EnFan$$
(30)

where:

EnTot: total energy consumption (kJ/kg-water).



**Figure 3.** *Flow chart of the simulation program.* 

c	irculating concurre	nt-flow drying simulation of rapeseed	
- Initial rapeseed conditions -		Reset	
Initial grain moisture content	0.23 dec, w.b.	Simulate and export data to Excel	
Initial grain temperature	22.8 oC	Simulated results	
Desired final moisture content	0.138 dec, w.b.	Drying time h	
		Number of pass	
Dryer specifications		Final moisture content %w.b.	
Capacity of dryer	200 kg	Drying rate %w.b./h	
Drying air flow rate	30 cmm/sq.m	Water removed rate kg/sq.m	
Grain velocity	5 m/h	Fan static pressure Pa	
		Fan power kVV/sq.m	- TA
Drying air and ambient cond	itions	Fan energy kJ/kg-water	
Drying air temperature	90 oC	Fuel energy kJ/kg-water	
Ambient air temperature	25.4 oC	Total energy consumption kJ/kg-water	
Ambient air relative humidity	0.716 dec		

#### Figure 4.

Interface of the simulation program RCDSim-LAD.

### 3.3 Psychrometric properties

#### 3.3.1 Saturated vapor pressure

$$P_s = r \frac{a + b \cdot T_k + c \cdot T_k^2 + d \cdot T_k^3 + e \cdot T_k^4}{f \cdot T_k - g \cdot T_k^2}$$
(31)

where:

 $\begin{array}{l} P_{s}: \mbox{ saturated vapor pressure (Pa).} \\ T_{k}: \mbox{ absolute temperature (K).} \\ r = 22105649.25; \mbox{ a } = -27405.526; \mbox{ b } = 97.5413; \mbox{ c } = -0.146244; \\ d = 0.12558 \times 10^{-3}; \mbox{ e } = -0.48502 \times 10^{-7}; \mbox{ f } = 4.34903; \mbox{ g } = 0.39381 \times 10^{-2}. \end{array}$ 

$$h = 0.6219 \cdot \frac{RH \cdot P_s}{P_{atm} - RH \cdot P_s} \tag{32}$$

h: absolute humidity (kg-water/kg-dry air). RH: relative humidity (dec). P<sub>atm</sub>: atmospheric pressure, P<sub>atm</sub> = 101,325 (Pa).

3.3.3 Specific volume

$$vs = 287 \cdot T_k \cdot \frac{0.6219 + h}{0.6219 \cdot P_{atm}}$$
(33)

vs.: specific volume (m<sup>3</sup>/kg).

A	В	C	D	E	F	G	Н		J	K	L
1		Concurre	ent flow d	rying simu	lation of r	apeseed					
2	1		(using 4th-on	rder Runge-Kut	tta method)		1				
3			1. IN	542	.đ.,						
4	Input data	a:									
5		Initial grain	moisture cor	ntent	23.00	%,w.b.					1
6		Initial grain	temperature	1	22.8	oC	1.15	Rapeseed ter	np. inside dryi	ng chamber	1
7		Drying air te	emperature		90	oC		65	1.9 92.9	(5)	
8		Ambient air	temperature		25.4	oC	T	op layer 🛶 Mid	. layer 🔶 Bot.	layer 🛶 Max. T	emp.
9		Ambient air	relative hum	idity	0.716	dec	45.0				
10		Air flow rat	e		30	cmm/m2	40.0				
11		Grain veloci	it <del>u</del>		5	m/h	40.0 -			*****	
10	Distant	Grant veloci	uy			11011	 ວີ	A state			-
12	Results of	humber of			20		<u> </u>	- and -			
13		First mainter	pass		12.52	07	25.0 -				
14		Final moistu	ire content		13.33	70,W.D.	20.0				-
15		Drying time	<u>.</u>		4.20	h	<b>E</b> 15.0 -				_
16		Drying rate			2.26	%w.b./h	<b>10.0</b>				
17		Water remo	ved rate		40.70	kg/m2	5.0 -				
18		Fan static p	ressure		1122	Pa	0.0 +				
19	1	Fan power			0.39	kW/m2	32	20 10 1A	\$ 3 3	5 10 to 1	\$
20	1	Fan energy			145.8	kJ/kg-water	- 100 - 100		Drying time	(h)	
21		Fuel energy			5153.2	kJ/kg-water					
22		Total energy	y consumptio	on	5299.0	kJ/kg-water					
23	1		5 55 5 56 5896								
24										(a) (a)	
25	Drying	Moisture	Drying	Grain		1	Rapeseed te	mperature in	side drying c	hamber	Exhaust a
the second s	Drying time	Moisture content	Drying temp.	Grain temp.		Time	Rapeseed te Top layer	mperature in Mid. layer	<b>side drying c</b> Bot. layer	<b>hamber</b> Max. temp.	Exhaust ai temp.
26	Drying time (h)	Moisture content (%,w.b.)	Drying temp. (oC)	Grain temp. (oC)		Time (h)	Rapeseed te Top layer (oC)	mperature in Mid. layer (oC)	<b>side drying c</b> Bot. layer (oC)	hamber Max. temp. (oC)	Exhaust ai temp. (oC)
26 27	Drying time (h)	Moisture content (%,w.b.)	Drying temp. (oC)	Grain temp. (oC)		Time (h)	Rapeseed te Top layer (oC)	mperature in Mid. layer (oC)	side drying c Bot. layer (oC)	hamber Max. temp. (oC)	Exhaust ai temp. (oC)
26 27 28	Drying time (h) 0.019	Moisture content (%,w.b.) 23.00	Drying temp. (oC) 90.0	Grain temp. (oC) 22.8		Time (h) 0.21	Rapeseed te Top layer (oC) 22.8	mperature in: Mid. layer (oC) 29.6 24.7	side drying c Bot. layer (oC) 29.2	hamber Max. temp. (oC) 29.6	Exhaust a temp. (oC) 29.4
26 27 28 29	Drying time (h) 0.019 0.038	Moisture content (%,w.b.) 23.00 22.84 23.78	Drying temp. (oC) 90.0 61.0 45.3	Grain temp. (oC) 22.8 26.2 28.2		Time (h) 0.21 0.42	Rapeseed te Top layer (oC) 22.8 25.5 27.5	mperature in: Mid. layer (oC) 29.6 31.7 23.2	side drying c Bot. layer (oC) 29.2 31.2	hamber Max. temp. (oC) 29.6 31.7	Exhaust a temp. (oC) 29.4 31.4
26 27 28 29 30	Drying time (h) 0.019 0.038 0.057	Moisture content (%,w.b.) 23.00 22.84 22.78	Drying temp. (oC) 90.0 61.0 46.3 29.7	Grain temp. (oC) 22.8 26.2 28.2 29.1		Time (h) 0.21 0.42 0.63	Rapeseed te Top layer (oC) 22.8 25.5 27.5 29.9	mperature ins Mid. layer (oC) 29.6 31.7 33.3 24.4	side drying c Bot. layer (oC) 29.2 31.2 32.6 23.7	hamber Max. temp. (oC) 29.6 31.7 33.3 24.4	Exhaust a temp. (oC) 29.4 31.4 32.9 240
26 27 28 29 30 31	Drying time (h) 0.019 0.038 0.057 0.076 0.076	Moisture content (%,w.b.) 23.00 22.84 22.78 22.74 22.74	Drying temp. (oC) 90.0 61.0 46.3 38.7 24.7	Grain temp. (oC) 22.8 26.2 28.2 29.1 29.5		Time (h) 0.21 0.42 0.63 0.84	Rapeseed te Top layer (oC) 22.8 25.5 27.5 28.9 20.0	mperature in: Mid. layer (oC) 29.6 31.7 33.3 34.4 25.2	side drying c Bot. layer (oC) 29.2 31.2 32.6 33.7 24.5	hamber Max. temp. (oC) 29.6 31.7 33.3 34.4 25.2	Exhaust a temp. (oC) 29.4 31.4 32.9 34.0 24.9
26 27 28 29 30 31 32	Drying time (h) 0.019 0.038 0.057 0.076 0.095	Moisture content (%,w.b.) 23.00 22.84 22.78 22.74 22.71 23.69	Drying temp. (oC) 90.0 61.0 46.3 38.7 34.7 23.5	Grain temp. (oC) 22.8 26.2 28.2 29.1 29.5 29.6		Time (h) 0.21 0.42 0.63 0.84 1.05	Rapeseed te Top layer (oC) 22.8 25.5 27.5 28.9 30.0 20.9	mperature in: Mid. layer (oC) 29.6 31.7 33.3 34.4 35.3 26.0	side drying c Bot. layer (oC) 29.2 31.2 32.6 33.7 34.5 25.1	hamber Max. temp. (oC) 29.6 31.7 33.3 34.4 35.3 26.0	Exhaust a temp. (oC) 29.4 31.4 32.9 34.0 34.8 25 4
26 27 28 29 30 31 32 33 24	Drying time (h) 0.019 0.038 0.057 0.076 0.095 0.114 0.124	Moisture content (%,w.b.) 23.00 22.84 22.78 22.74 22.74 22.71 22.69 23.67	Drying temp. (oC) 90.0 61.0 46.3 38.7 34.7 32.5 21.2	Grain temp. (oC) 22.8 26.2 28.2 29.1 29.5 29.6 20.6		Time (h) 0.21 0.42 0.63 0.84 1.05 1.26	Rapeseed te Top layer (oC) 22.8 25.5 27.5 28.9 30.0 30.8 21.4	mperature in: Mid. layer (oC) 29.6 31.7 33.3 34.4 35.3 35.9 26.4	side drying c Bot. layer (oC) 29.2 31.2 32.6 33.7 34.5 35.1 25.5	hamber Max. temp. (oC) 29.6 31.7 33.3 34.4 35.3 36.0 26.5	Exhaust a temp. (oC) 29.4 31.4 32.9 34.0 34.8 35.4 25.0
26 27 28 29 30 31 32 33 34 25	Drying time (h) 0.019 0.038 0.057 0.076 0.095 0.114 0.134 0.452	Moisture content (%,w.b.) 23.00 22.84 22.78 22.74 22.71 22.69 22.67 23.65	Drying temp. (oC) 90.0 61.0 46.3 38.7 34.7 32.5 31.3 20.5	Grain temp. (oC) 22.8 26.2 28.2 29.1 29.5 29.6 29.6 29.6		Time (h) 0.21 0.63 0.84 1.05 1.26 1.47 4.69	Rapeseed te           Top layer           (oC)           22.8           25.5           27.5           28.9           30.0           30.8           31.4	mperature in: Mid. layer (oC) 29.6 31.7 33.3 34.4 35.3 35.9 36.4 26.9	side drying c Bot. layer (oC) 29.2 31.2 32.6 33.7 34.5 35.1 35.5 25.0	hamber Max. temp. (oC) 29.6 31.7 33.3 34.4 35.3 36.0 36.5 26.9	Exhaust a temp. (oC) 29.4 31.4 32.9 34.0 34.8 35.4 35.9 25.2
26 27 28 29 30 31 32 33 34 35 26	Drying time (h) 0.019 0.038 0.057 0.076 0.095 0.114 0.134 0.153 0.472	Moisture content (%,w.b.) 23.00 22.84 22.78 22.74 22.74 22.71 22.69 22.67 22.66	Drying temp. (oC) 90.0 61.0 46.3 38.7 34.7 32.5 31.3 30.5 20.0	Grain temp. (oC) 22.8 26.2 28.2 29.1 29.5 29.6 29.6 29.6 29.5 29.6		Time (h) 0.21 0.42 0.63 0.84 1.05 1.26 1.26 1.47 1.68	Rapeseed te Top layer (oC) 22.8 25.5 27.5 28.9 30.0 30.0 30.8 31.4 31.8	mperature im Mid. layer (oC) 29.6 31.7 33.3 34.4 35.3 35.9 36.4 36.8	side drying c Bot. layer (oC) 29.2 31.2 32.6 33.7 34.5 35.1 35.5 35.9 26.2	hamber Max. temp. (oC) 29.6 31.7 33.3 34.4 35.3 36.0 36.5 36.9 27.2	Exhaust a temp. (oC) 29.4 31.4 32.9 34.0 34.8 35.4 35.9 36.2 26.5
26 27 28 29 30 31 32 33 34 35 36 27	Drying time (h) 0.019 0.038 0.057 0.076 0.095 0.114 0.134 0.153 0.172 0.405	Moisture content (%,w.b.) 23.00 22.84 22.78 22.74 22.74 22.71 22.69 22.67 22.66 22.64 22.64 22.64	Drying temp. (oC) 90.0 61.0 46.3 38.7 34.7 32.5 31.3 30.5 30.0 30.0 20.7	Grain temp. (oC) 22.8 26.2 28.2 29.1 29.5 29.6 29.6 29.6 29.5 29.5 29.3		Time (h) 0.21 0.42 0.63 0.84 1.05 1.26 1.26 1.47 1.68 1.89 2.10	Rapeseed te           Top layer           (oC)           22.8           25.5           27.5           28.9           30.0           31.4           31.8           32.2           20.4	mperature in: Mid. layer (oC) 29.6 31.7 33.3 34.4 35.3 35.9 36.4 36.8 37.1 37.4	side drying c Bot. layer (oC) 29.2 31.2 32.6 33.7 34.5 35.1 35.5 35.9 36.2 26.4	hamber Max, temp. (oC) 29.6 31.7 33.3 34.4 35.3 36.0 36.5 36.9 37.2 27.4	Exhaust a temp. (oC) 29.4 31.4 32.9 34.0 34.8 35.4 35.4 35.4 36.2 36.2 36.5
26 27 28 29 30 31 32 33 33 34 35 36 37 37	Drying time (h) 0.019 0.038 0.057 0.076 0.095 0.114 0.134 0.153 0.172 0.172	Moisture content (%,w.b.) 23.00 22.84 22.78 22.74 22.71 22.69 22.67 22.66 22.64 22.63 22.64 22.63	Drying temp. (oC) 90.0 61.0 46.3 38.7 34.7 32.5 31.3 30.5 30.0 29.7 29.4	Grain temp. (oC) 22.8 26.2 29.5 29.6 29.6 29.6 29.6 29.6 29.5 29.3 29.2 29.3		Time (h) 0.21 0.42 0.63 0.84 1.05 1.26 1.47 1.68 1.89 2.10 2.24	Rapeseed te Top layer (oC) 22.8 25.5 27.5 28.9 30.0 30.8 31.4 31.8 32.2 32.4	mperature im Mid. layer (oC) 29.6 31.7 33.3 34.4 35.3 35.9 36.4 36.8 37.1 37.4 37.4	side drying c Bot. layer (oC) 29.2 31.2 32.6 33.7 34.5 35.1 35.5 35.5 35.9 36.2 36.4 26.6	hamber Max. temp. (oC) 29.6 31.7 33.3 34.4 35.3 36.0 36.5 36.9 37.2 37.4 27.6	Exhaust a temp. (oC) 29.4 31.4 32.9 34.0 34.8 35.4 35.4 35.9 36.2 36.5 36.7 36.7

#### **Figure 5.** *Simulated data with excel interface.*

Using MATLAB 7.3.0., Simulated results were exported to Excel (**Figure 5**) by clicking the button "Simulate and export data to Excel" on the interface of the simulation program (**Figure 4**).

In excel interface, besides the output data in the simulation program were listed in **Table 1**, the drying air temperature, rapeseed temperature, and moisture content of rapeseed in the drying process versus drying time are also displayed and automatically represented by graphs, in which the rapeseed temperature at the top layer, middle layer, bottom layer, and the maximum rapeseed temperature in the drying chamber versus drying time are also displayed.

## 4. Model validation

#### 4.1 Pilot-scale concurrent-flow dryer

In order to verify a fitness of simulation program, a pilot-scale concurrent-flow rapeseed dryer with capacity of 200 kg/batch was designed and manufactured. The dimension of the dryer is shown in **Figure 6**, and the structural principle of the dryer is shown in **Figure 7**. The pilot-scale rapeseed dryer includes a drying tower with grain inlet section, plenum section, and drying section; burner; drying fan; variable speed discharge augers; and bucket elevator for circulating the grains.

The hot air is supplied by a kerosene jet burner; after going through the mixed chamber, the drying air will enter the dryer through plenum section. Rapeseed and drying air are moving the same direction until drying the air out by force of suction



#### **Figure 6.** *Technical drawing of pilot-scale concurrent-flow dryer.*

centrifugal fan through five exhaust air ducts. Rapeseed flow rate is controlled by two variable speed discharge augers. Rapeseed is out the dryer by discharge augers. Then, the grains are circulated by bucket elevator from the top of the dryer and flow down the vertical drying chamber.

The dimensions of the pilot-scale concurrent-flow dryer are shown in detail in **Figure 6**.

## 4.2 Experimental design

During the experiment the drying air temperature and grain temperature are continuously measured by temperature sensors (Thermocouple T-type, Omega, USA). The total of 16 temperature sensors was arranged at necessary positions inside and outside the dryer (**Figure 7**). Data from sensors were transferred to data logger system. Two computers were used to record the temperature data from the data logger (Datascan 7327, UK).

In the plenum section, drying air temperature input was measured by three sensors No. 1–3. In exhaust air ducts, two sensors at upper ducts (No. 10–11) and two sensors at lower ducts (No. 12–13) were arranged to measure exhaust air temperature. In the drying chamber, six sensors (No. 4–9) were arranged at six positions in the cross-section of the drying chamber to measure the temperature of grains. In two discharge augers, two sensors (No. 14–15) were arranged above the two discharge augers to measure discharge rapeseed temperature (rapeseed temperature after drying). To measure ambient air temperature, one temperature sensor (No. 16) was arranged outside the dryer (**Table 2**).

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Figure 7.

Design layout for the temperature and relative humidity sensor locations in the pilot-scale concurrent-flow dryer.

Temperature measurement			Sensors
Drying air temperature	Inlet	3	No. 1–3
	Outlet	4	No. 10–13
Rapeseed temperature	Drying chamber	6	No. 4–9
	Discharge	2	No. 14–15
Ambient air temperature		1	No. 16
Relative humidity measurement	:		
Ambient air relative humidity		1	No. 17
Exhaust air relative humidity		1	No. 18

#### Table 2.

Temperature sensors distribution and hygrometer used in the experiment.

Two hygrometers (MTH4100, Sanyo, UK, 10 - 99%,  $\pm 2.5\%$ ) were installed to record the ambient air relative humidity (No. 17) and exhaust air relative humidity (No. 18) (**Table 2**).

#### Current Drying Processes

In both experiments, grain flow velocity was set up at 5 m/h; this value is equivalent to the mass of circulated rapeseed which is 1000 kg/h. The grain flow velocity is controlled by two discharge rollers. The rotation of discharge rollers was 3.5 rpm. The rotation of discharge rollers was controlled by an inverter (S500, Mitsubishi, Japan).

A centrifugal suction fan 1 HP with air flow rate 30 cmm/m<sup>2</sup> [12] was used for sucking the exhaust drying air. An anemometer (Velocicalc-Plus, TSI, USA) was used to measure the drying air velocity.

The jet burner using kerosene (OL-3, Daewon, Korea) was used for heating drying air. The burner can be raised to the temperature of drying air up to 140°C. A temperature sensor (PT-100  $\Omega$ ) was installed at the influx duct to control the burner, and a temperature control equipment (HSD-V2, Hansung, Korea) was used. An electric balance (A-200, Cass, Korea, accuracy 0.01 kg) was used to weigh the mass of Kerosene loss by drying process.

The dimension of drying chamber (height  $\times$  length  $\times$  width) is 0.5 m  $\times$  0.7 m  $\times$  0.5 m. Height of tempering section is 0.5 m. In both experiments, rapeseed samples using are Spring rapeseed, variety Sunmang F1-hybrid, were harvested in June in Jeonnam-do, Yeonggwang-gun. The samples of 200 kg were cleaned and stored in a refrigerator at a temperature of 4°C [13]. The initial moisture content of samples in Test 1 is 23.0% and in Test 2 is 23.2% (**Table 3**).

#### **4.3 Experimental results**

In both experiments, there are a difference in drying air temperature in the plenum chamber. The drying air temperature is highest at the position in front of the plenum, and lowest at back of plenum. In Test 1, the average temperature of drying air in the plenum section is 96.9, 84.2, and 83.9°C at the front, middle, and back of the plenum, respectively. In Test 2, the average temperature of drying air in plenum section is 128.1, 111.3, and 106.1°C at front, middle, and back of plenum, respectively (**Table 4**). The average temperature of drying air in the plenum chamber during drying process is 89.4 and 116.8°C for Test 1 and Test 2, respectively (**Figure 8**).

The temperature of rapeseed during drying at discharge augers (**Figure 9**) and the temperature of air at exhaust ducts (**Figure 10**) for both Test 1 and Test 2 are fairly uniform. Detailed drying conditions in Test 1 and Test 2 shown in **Table 5** and results of rapeseed drying in a pilot-scale dryer were summarized in **Table 6**.

Rapeseed	Test 1	Test 2
Initial weight (kg)	200	200
Initial moisture content (% w.b.)	23.0	23.2
Initial grain temperature (°C)	22.8	24.7

#### Table 3.

Initial rapeseed conditions.

Test no.	Drying air temperature (°C)			
	Front	Middle	Back	
Test 1	96.9	84.2	83.9	
Test 2	128.1	111.3	106.1	

#### Table 4.

Drying air temperature in the plenum chamber.

After the experiment was completed, dried rapeseed samples were sealed in double-layer polythene bags for 24 h to reach ambient conditions [14]. The samples were then tested for germination. The germination tests were conducted according



**Figure 8.** *Average variation of drying air temperature during drying process.* 



**Figure 10.** *Temperature of exhaust drying air in test 1 and test 2.* 

to protocols described for the standard germination test [15]. The average germination percentages of Test 1 and Test 2 are 94.7 and 84.5%, respectively [16].

#### 4.4 Model validation

The simulation program was validated by comparison results of numerical model with experimental data of pilot-scale concurrent-flow dryer as described. The input data of simulation program were entered in accordance with the data of the actual experiment, such as initial rapeseed conditions, dryer specification, and drying air and ambient air conditions. The fitness of simulated results with measured results was evaluated based on the coefficient of determination (R<sup>2</sup>) and the root mean square error (RMSE).

The  $R^2$  of moisture content versus drying time in Test 1 and Test 2 were 0.994 and 0.997, respectively. The RMSE of moisture content in Test 1 and Test 2 were 0.334 and 0.506%w.b., respectively. The comparison of the measured and

Test No.	Average drying air temperature (°C)	Air flow rate (cmm/m <sup>2</sup> )	Ambient air temperature (°C) Ave. (min–max)	Ambient relative humidity (%) Ave. (min– max)
Test 1	89.4	30	25.4 (24.2–26.4)	71.6 (67.1–75.3)
Test 2	116.8	25	28.6 (26.7–31.4)	63.4 (60.8–68.0)

#### Table 5.

Drying conditions for drying tests.

Experimental results	Test 1	Test 2
Initial moisture content (% w.b.)	23.0	23.2
Final moisture content (% w.b.)	13.8	11.4
Drying time (h)	3.90	4.22
Drying rate (% w.b./h)	2.38	2.80
Fuel consumption (kJ/kg-water)	4915	4831
Initial germination rate (%)	94.7	84.5



**Figure 11.** *Measured and simulated moisture content in test 1.* 

simulated moisture content during drying process for Test 1 is shown in **Figure 11** and for Test 2 shown in **Figure 12**.

The analytical results showed the good fitness between simulated moisture content and measured moisture content for both Test 1 and Test 2. This result showed the good agreement of the simulation program for predicting the moisture content of rapeseed in concurrent-flow dryer.

The simulated temperature of rapeseed during drying process has a good correlative with the experimental data. The R<sup>2</sup> of rapeseed temperature are 0.904 and 0.925 in Test 1 and Test 2, respectively. The RMSE of rapeseed temperature are 1.15 and 1.77°C in Test 1 and Test 2, respectively. The comparison of the measured and simulated temperature of rapeseed for Test 1 is shown in **Figure 13** and for Test 2 shown in **Figure 14**. The analytical results showed that simulated values have a very good fitness to measured values by experiment.

The discharge rapeseed temperature of the simulation program tends to be higher than the measured values during drying process. However, the average differences between measured and simulated values are small. It showed a good fitness between the values of the model and the values of the experiments.

The drying time, drying rate, fuel energy consumption, and germination ratio of rapeseed after drying were investigated. The comparison of the measured and simulated results of both Test 1 and Test 2 was listed in **Table 7**.



Figure 13. Measured and simulated temperature of rapeseed in test 1.



Figure 14.

Measured and simulated temperature of rapeseed in test 2.

Test 1	Measured	Simulated	Difference (%)
Final moisture content (% w.b.)	13.8	13.5	2.2
Drying rate (% w.b./h)	2.38	2.26	5.04
Fuel energy (kJ/kg-water)	4915	5153	4.62
Drying time (h)	3.9	4.2	7.14
Germination ratio (%)	94.7	96.5	1.87
Test 2	Measured	Simulated	Difference (%)
Final moisture content (% w.b.)	11.4	10.8	5.17
Drying rate (% w.b./h)	2.80	2.95	5.08
Fuel energy (kJ/kg-water)	4831	4417	8.57
Drying time (h)	4.22	4.2	0.47
Germination ratio (%)	84.5	92.5	8.64

#### Table 7.

Measured and simulated results of test 1 and test 2.

The difference between measured value and simulated value of final moisture content were 2.2 and 5.17%; drying rate were 5.04 and 5.08%; drying time were 7.14 and 0.47%; and germination ratio were 1.87 and 0.47%. The simulated values of fuel energy consumption for drying were 4.62 and 8.57% lower than the measured values for Test 1 and Test 2, respectively. The differences are derived from the sequential changes in drying air temperature, ambient temperature, and drying air humidity of the simulation model and experiment conditions. In general, there is a good fitness between measured values by experiment and simulated values from the simulation program for all of the output parameters such as final moisture content, drying time, drying rate, fuel energy, and germination ratio at the different experiment conditions.

### 5. Conclusions

Mathematical modeling for rapeseed drying on concurrent-flow dryer was built based on energy and mass transfer balances applied for both fluid and solid phases

of a concurrent-flow dryer. Energy balances and mass balances are written on a differential volume located at an arbitrary location in the grain bed. The mathematical model consists of a set of four partial differential equations in four independent variables including air humidity, air temperature, grain temperature, and grain moisture content.

A computer simulation program for circulating concurrent-flow rapeseed dryer was developed using these models along with a detailed description of the program. The simulation program can predict the drying time, drying rate, drying air humidity and temperature, grain temperature and moisture content during drying process, water removal rate, drying fan parameters, germination ratio, fuel energy, and total energy consumption.

To evaluate a fitness of simulation program, a pilot-scale concurrent-flow dryer with a capacity of 200 kg/batch was designed, manufactured, and tested. Two drying experiments were conducted. The output parameters of the simulation program were compared and analyzed with experiment data.

The RMSE of simulated moisture contents ranged from 0.334 to 0.506%w.b. with the coefficient of determinations ranging from 0.994 to 0.997. The RMSE of simulated rapeseed temperatures ranged from 1.15 to 1.77°C with the coefficient of determinations ranging from 0.904 to 0.925. The experimental drying rates were 2.38 and 2.80% w.b./h. The difference between simulated value and measured value of drying rate were 5.04 and 5.08%; drying time were 7.14 and 0.47%; and germination ratio were 1.87 and 0.47%. The simulated fuel energy consumption for drying were 4.62 and 8.57% lower than the experimental values.

The analytic results showed that the simulation results have good fitness with experimental data. So, the mathematical modeling and the simulation program were proved their reliability and were shown to be a convenient tool for simulation of rapeseed drying in circulating concurrent-flow dryer.

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