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Simulation of Wheat Circulating Cross-flow Dryer

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Abstract

Purpose: In Korea, wheat is dried using circulating cross-flow grain dryers. However, there is no research on wheat drying which can be utilized for the dryers. Therefore, this study developed and evaluated a simulation of the circulating cross-flow dryer, and examined the effects of various factors on drying performance. **Methods:** The simulation program was developed using drying models and was evaluated against wheat-drying experiments with a dryer having a 30-ton capacity. The influence of drying temperature, air volume, and grain falling rate on drying performance were examined through the simulation. **Results:** The experimental results validated the simulation program by showing the same root mean square error (RMSE) for moisture content (0.286%) and drying rate (0.056%/h) in both the experimental data and the simulation values. The appropriate wheat-drying parameter values, considering drying conditions, were determined to be 50°C for drying temperature, 500 m^3/min for air volume, and a grain falling rate of 36.0 m^3/h. **Conclusions:** The developed simulation program for circulating cross-flow dryers analyzed the influences of performance factors such as drying temperature, air volume, and falling rate on drying performance.

Keywords: Circulation, Cross-flow, Grain dryer, Simulation, Wheat

Introduction

Per capita rice consumption in Korea declined from 93.6 kg (in 2000) to 67.2 kg (in 2013), but wheat consumption increased steadily in that time by more than 30.0 kg. However, the self-sufficiency rate for wheat is only 1.1%, which is much less than that of rice (90%) (MAFRA, 2014). Wheat consumption and imports have constantly increased because of the changes in eating habits from rice to wheat, and Korea imported four million tons in 2009 (Park et al., 1999; Nam et al., 2000). Interest in domestic wheat production and processing are increasing, along with recent interest in food safety. Wheat is dried after harvesting; therefore, inappropriate drying processes can cause negative effects on both storage and processing. Wheat is harvested at a moisture content of 19.0%, w.b. and dried with hot air to less than 13%, w.b. for excellent storability and processing (Walde et al., 2002). Circulating cross-flow dryers are mainly used for grain drying in Korea. They have a drying chamber and a tempering chamber. Drying is completed with the repetition of the drying and tempering processes: while grains fall vertically, drying air blows through the falling grains in the drying chamber, and the uneven moisture content and temperature inside the grain layers are mitigated in the tempering chamber (Keum et al., 1987). The performance of the circulating cross-flow dryer is evaluated in terms of the drying speed and the energy consumed by drying temperature, tempering duration, drying layer thickness, circulation speed, and blowing air volume (Kim and Han, 2008). The drying speed of wheat is known to be slower than that of rice; however, there is no research on wheat drying that can be applied to the dryers in Korea (Keum, 2008). To determine the drying temperature, air volume, and circulation speed for circulating cross-flow dryers, drying performance

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should be investigated using various performance factors (Brooker et al., 1992; Keum et al., 1987). The performance factors can be examined by experiments or mathematical models, but simulation reduces time and expense (Kim and Han, 2008). Because the drying characteristics of wheat differ significantly depending on air volume, circulation speed, drying air, and physical properties, it is difficult to investigate the factors with experiments considering all of these drying conditions (Han et al., 2010). Therefore, the purposes of this study are to develop and evaluate a simulation program for wheat dryers based on a simulation model of a circulating cross-flow dryer, and to examine the influence of the performance factors on the drying process.

Materials and Methods

Simulation model

Drying model

In the circulating cross-flow dryer, grains flow through the drying chamber vertically by gravity, and drying air passes through the grain layers horizontally. The grains passing through the drying chamber are carried to the tempering chamber via a bucket elevator. The grains from the tempering chamber are circulated continuously in the drying chamber to reach the target moisture content, by repeating the processes of drying, circulating, and tempering (Bakker-Arkema et al., 1974; Keum et al., 1987). Moisture content (M), grain temperature (θ), and relative humidity (H) change when drying air with temperature (T) and relative humidity (H) passes through the thin grain layer horizontally. The drying air with temperature (T) and relative humidity (H) that passes through the grain layer evaporates the moisture content (ΔM) from grain with moisture content (M) and temperature (θ) for Δt hours. Therefore, the absolute temperature of the drying air becomes H+ΔH, and the moisture content of grain changes to M–ΔM. In addition, the temperature (T) of the drying air changes to T–ΔT according to the freezing effect caused by grain temperature rise and the evaporation of moisture content. The condition of the drying air that passed through the thin grain layer became an initial drying air condition for the next thin grain layer. A thin dried grain layer moves down as much as Δy during Δt hours, and the drying process repeats. (Kim, 2003)

$$\frac{\partial T}{\partial x} = \frac{h_c a}{G_a(G_a + C_v H)}(T - \theta) \tag{1}$$

$$\frac{\partial \theta}{\partial y} = \frac{h_c a}{G_g(C_g + C_w M)}(T - \theta) + \frac{h_{fg} + C_v(T-\theta)}{G_g(C_g + C_w M)} G_a \frac{\partial H}{\partial x} \tag{2}$$

$$\frac{\partial H}{\partial x} = \frac{G_g}{G_a} \cdot \frac{\partial_M}{\partial y} \tag{3}$$

$$\frac{\partial M}{\partial x} = \text{ thin layer drying equation} \tag{4}$$

where T : air temperature (°C)
h_c : convection heat transfer coefficient (kJ/m^2·K·h)
a : specific surface area of grain (m^2/m^3)
G_a : air flow rate (kg/h·m^2)
C_a : specific heat of dry air (kJ/kg·K)
C_g : specific heat of dry grain (kJ/kg·K)
C_v : specific heat of water vapor (kJ/kg·K)
H : enthalpy of dry air (kJ/kg)
θ : grain temperature (°C)
G_g : grain flow rate (kg/h·m^2)
M : grain moisture content (dec., d.b.)
C_w : specific heat of water in grain (kJ/kg·K)
h_{fg} : vaporization latent heat of water within grain (kJ/kg)
x : axis of air flow (m)
y : axis of grain flow (m)

Thin layer drying model, equilibrium moisture content, and latent heat of evaporation

Equation (5) represents the equilibrium moisture content model, developing experimental constants by applying the static equilibrium moisture content of the experimental data to the Chung–Pfost model (ASABE Standard, 2004). The thin layer drying model is used to analyze the drying rate for a thin layer of wheat. Then, after repeating the simulation of the thin layer drying model, the drying rate for a thick layer of wheat can be calculated. Therefore, the thin layer drying model is most important for investigating the drying rate for wheat, and it uses equation (6), which is the Page model (Keum, 2008).

$$M_e = b_1 - b_2 \ln[-(T + b_3)\ln RH] \tag{5}$$

$$MR = \exp(-P \cdot t^Q) \tag{6}$$

where, $MR(t)$: moisture ratio (dimensionless) $(M(t)-M_e)/(M_o-M_e)$

M_e : equilibrium moisture content (dec., d.b.)

$M(t)$: moisture content (dec., d.b.)

RH : equilibrium moisture content (dec.)

T : drying air temperature (°C)

M_o : initial moisture content (dec., d.b.)

t : drying time (min)

b_1 : 0.27908, b_2 : 0.042360, b_3 : 35.662

P : $2.1217\times10^{-9}\cdot e^{[0.0492\times(T+273)]}$

Q : 1

The latent heat of evaporation (h_{fg}) was calculated with equation (7), which Keum (2008) suggested.

$$h_{fg}=(2502.535-2.386\cdot T)\cdot[1+2.8868\cdot e^{(-23.6263\cdot M)}] \quad (7)$$

Other model

The other model used in the simulation is from the ASABE Standard (2004), and product density, specific heat, convective heat transfer coefficient, and the air resistance value of the grain layer are used. Energy consumption was calculated from the flow rate of the drying air (Kato, 1983). The simulation program developed by Matlab (R2012) consists of 16 sub-programs that calculate the equilibrium moisture content, and change the properties of humid air. The initial input values are the dryer specification, initial wheat condition, ambient air condition, and drying air condition. The wheat conditions are input weight, initial moisture content, final moisture content, and flow rate. The number of circulation cycles, tempering time, drying time, drying rate, drying moisture content, grain temperature, and energy consumption are calculated as output values.

Verification of the simulation model

Wheat, harvested at Jeonbuk province in June, 2014, was conveyed to the storage facility, and foreign matters were screened by a paddy cleaner. The moisture content of the wheat was 18.7%, w.b. The capacity of the circulating cross-flow dryer used in this study was 30 tons, and the dryer consisted of a drying chamber, a tempering chamber, an outlet, an elevator, a burner, a dust collection unit, and a control unit. The initial weight of wheat was 29.8 tons, and the temperature of the drying air was 55°C. After drying, 500 g of sample wheat were collected at one-hour intervals, and the moisture content of the sample was measured by the 10 g-130°C-19 hour drying method of constant temperature and normal pressure. The drying air temperature and grain temperature were measured by a Thermocouple (T-type, OMEGA, USA) at each measurement point: 12 points at the drying air inlet (for drying air temperature measurement), one point at the grain outlet (for grain temperature measurement), two points in front of the blower (for temperature measurement of drying air passing through the drying chamber), and one point in ambient air. A data collection device (MX110, Yokogawa, Japan) was used to save the data on a PC at intervals of 30 seconds. Table 1 shows the drying conditions for evaluating the simulation: 29.8 tons of initial wheat weight, 24.3°C of initial grain temperature, 22.8°C of mean ambient air temperature, 45.0% of mean ambient relative humidity, 53.2°C of drying temperature, 37.3 m^3/h of grain circulation speed, and 420 m^3/min of air volume.

Table 1. Drying conditions used for the validation test of simulation program

Variety of wheat	Soo Ahn
Input grain weight (ton)	29.8
Initial moisture content (%, w.b.)	18.7
Initial grain temperature (°C)	24.3
Ambient temperature (°C)	22.8
Ambient relative humidity (%)	45.0
Drying air temperature (°C)	53.0
Grain flow rate (m^3/h)	37.3
Airflow rate (m^3/min)	420

Drying Performance Factors

The effects of drying conditions on drying speed and energy consumption were analyzed by changing the drying air temperature, air volume, and falling rate in the simulation of the circulating cross-flow dryer. Table 2 shows the drying conditions: 30 tons of dryer capacity, 20.0°C of initial grain and ambient temperatures, 26.0%, w.b. of initial moisture content, and 13.0%, w.b. of final moisture content. Six levels of drying temperatures (40, 45, 50, 55, 60, and 65°C), seven levels of grain falling rates (32, 34, 36, 38, 40, 42, and 44 m^3/h), and six levels of air volumes (10, 14, 18, 22, 26, and 30 m^3/min·ton) were determined. The simulation was analyzed with reference values: 55°C of drying temperature, 38 m^3/h of grain falling rate, and 18 m^3/min·ton of air volume.

Table 2. Drying conditions for wheat drying simulation

Capacity of grain dryer (ton)	30.0
Size of drying chamber (m)	1.8 × 2.5 × 0.23 (H × L × W)
Initial moisture content (%, w.b.)	26.0
Final moisture content (%, w.b.)	13.0
Initial grain temperature (°C)	20.0
Ambient temperature (°C)	20.0
Drying air temperature (°C)	40, 45, 50, 55, 60, 65
Drying air relative humidity (%)	50.0
Grain flow rate (m^3/h)	32, 34, 36, 38, 40, 42, 44
Airflow rate (m^3/min·ton)	10, 14, 18, 22, 26, 30

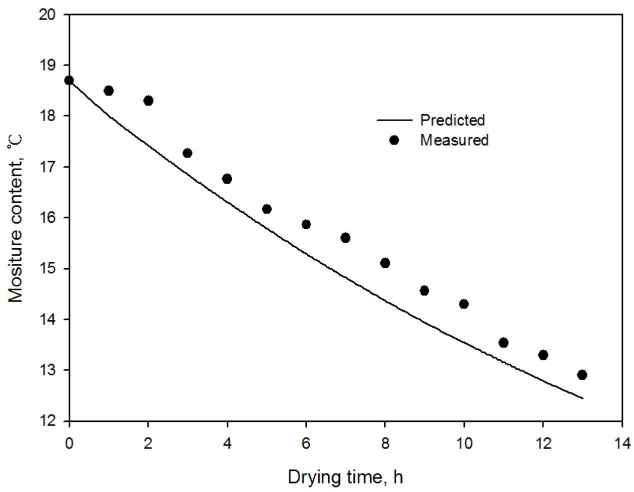

Figure 1. Comparison of measured and predicted moisture content.

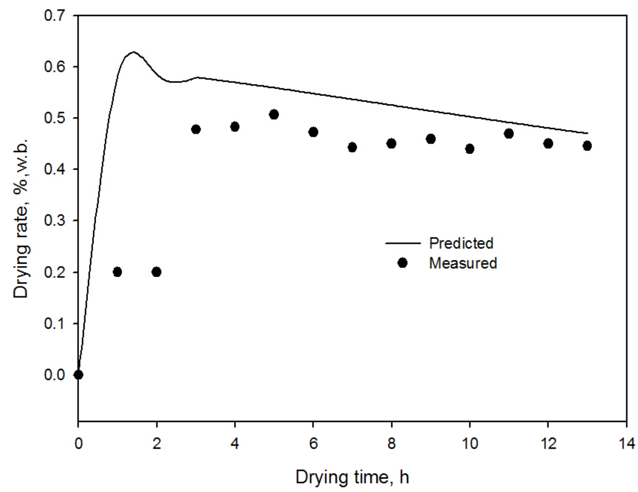

Figure 2. Comparison of measured and predicted drying rate.

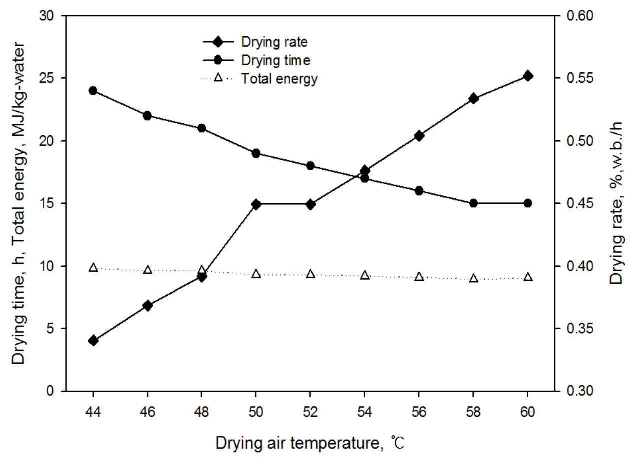

Figure 3. Effect of drying air temperature on drying time and drying rate.

Results and Discussion

Verification of the simulation model

Figures 1 and 2 compare the changes in moisture content and drying rate, based on drying time, between the experimental data and predicted values from the simulation. Moisture content values from both sets of data had a tendency similar to the drying rate values, and the root mean square error (RMSE) of the moisture content and the drying rate were 0.286% and 0.056%/h, respectively. The moisture content value of the predicted model was lower than that of the experimental data, while the drying rate value of the predicted model was higher than that of the experimental data. The drying temperature of the experimental data was higher than the predicted value by 53.2°C, and the drying speed of the experimental data was fast. Therefore, the simulation program predicted the changes in the moisture content and drying rate during wheat drying.

Effects of drying temperature on drying performance

Figure 3 shows the drying rate, drying time, and energy consumption at various drying temperatures. The drying rate increased with increasing temperature, but drying time and energy consumption did not changed owing to the reduction in the number of circulation cycles. The number of needed circulation cycles was reduced at around 50°C of drying temperature, which influenced the drying rate. Therefore, a drying temperature of 50°C is appropriate, considering the drying rate and drying time.

Effects of air volume on drying performance

Figure 4 shows the drying rate, drying time, the number of grain circulation, and energy consumption based on the changes of air volume. The drying rate and energy

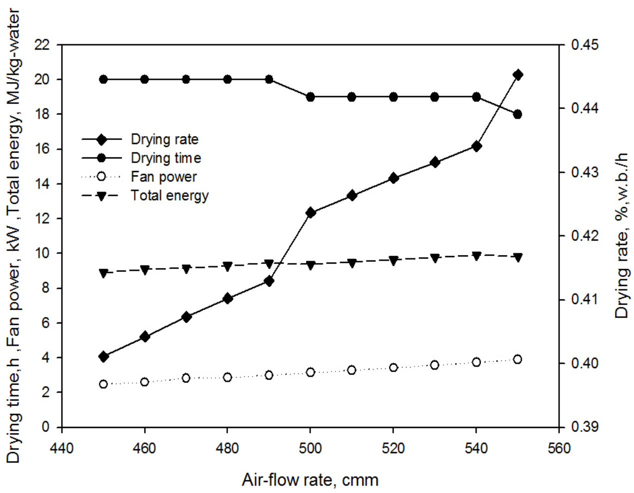

Figure 4. Effect of drying air temperature on drying time and drying rate.

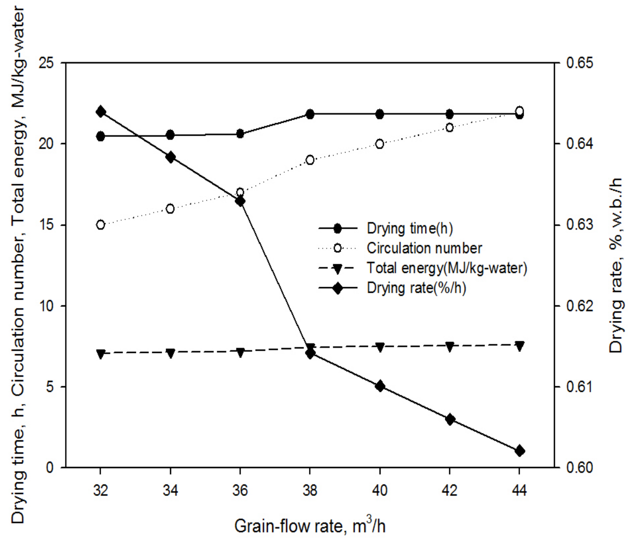

Figure 5. Effect of grain flow rate on drying time, circulation cycle number, total energy, and drying rate.

consumption increased with an increase in air volume, but drying time decreased with an increase in air volume. At around 500 m^3/min, the drying rate increased dramatically, and drying time decreased. Thus, 500 m^3/min of air volume can be considered appropriate for wheat drying, even though the same performance was observed above 500 m^3/min. Supplying high air volume might be efficient for drying, but it also increased the energy consumption and dust collection expense. Therefore, proper air volume should be determined for wheat drying.

Effects of grain flow rate on drying performance

Figure 5 shows the changes in drying rate, drying time, the number of circulation cycles, and energy consumption based on various grain flow rates. Drying time, the number of circulation cycles, and energy consumption increased with increased grain flow rate, and drying rate decreased with an increase in grain flow rate. With a grain falling rate of over 36.0 m^3/h, the drying rate decreased, and drying time increased. Energy consumption also increased with a 36.0 m^3/h or more grain flow rate. Therefore, 36.0 m^3/h of grain flowing is considered appropriate for wheat drying.

Conclusions

This study used the drying model, thin layer drying model, equilibrium moisture content, latent heat of evaporation, and another model to develop a simulation model for a circulating cross-flow wheat dryer. This study also verified the simulation program through experiments, and examined the effects of performance factors such as drying temperature, air volume, and flow rate on drying performance.

(1) This study developed a simulation model for a circulating cross-flow wheat dryer using the drying model, thin layer drying model, equilibrium moisture content, latent heat of evaporation, and another model.
(2) Drying experiments using a circulating cross-flow dryer with a capacity of 30.0 tons were conducted to evaluate the developed simulation. The results validated the simulation program by showing the same RMSEs of moisture content (0.286%) and drying rate (0.056%/h) in the experimental data and the simulation values.
(3) Effects of drying temperature, air volume, and grain flow rate on drying performance were examined using the simulation program. 50°C of drying temperature, within the range of 40 – 65°C was appropriate, considering the drying rate and drying time.
(4) 500 m^3/min of airflow rate for wheat drying was appropriate, because above this value the airflow rate showed an increased drying rate and decreased drying time. 36.0 m^3/h of grain flow rate was appropriate for wheat drying, considering drying rate and energy consumption.

Conflict of Interest

The authors have no conflicting financial or other interests.

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