

APPLICATION AND OPERATION OF PULSED FLUID BED DRYERS IN DRYING SEEDS

Summary

The article describes aspects of drying corn in a classic pulsed fluid bed dryer (PFB) and a spouted pulsed fluid bed dryer (SPFB). Experimental results demonstrate a modest difference in drying kinetics and time between the PFB and SPFB for the same amount of seeds. Analysis of data showed that drying kinetics is dependent on the temperature, bed height and the frequency of the disc in the gas distributor. Drying kinetics was modeled mathematically using classic models and the best correlation was obtained for the modified Page's model. A modification of the Page's model was proposed which led to a 97.6% and 99.4% correlation between experimental and calculated values of moisture content for PFB and SPFB, respectively.

Key words: pulsed fluid bed dryer, kinetics of drying, fluidized bed

ZASTOSOWANIE APARATÓW PULSOFLUIDYZACYJNYCH DO SUSZENIA NASION ZBÓŻ

Streszczenie

Artykuł zawiera aspekty suszenia nasion kukurydzy w klasycznym układzie pulsofluidalnym (PFB) oraz układzie pulsofluidalnym fontannowym (SPFB). Wyniki badań wskazują, że dla tej samej masy materiału w komorze suszenia nie ma istotnych różnic w czasie suszenia między klasycznym a fontannowym złożem pulsofluidyzacyjnym. Ustalono, że na kinetykę suszenia oprócz temperatury gazu i wysokości złoża wpływa również częstotliwość obrotu tarczy rozdzielacza. Do opisu kinetyki suszenia wykorzystano klasyczne modele matematyczne. Najlepsze dopasowanie modelu do danych eksperymentalnych uzyskano dla modyfikowanych modeli Page'a. Zaproponowano modyfikację modelu Page i uzyskano model wyjaśniający 97,6% wyjaśnionej zmienności wilgotności materiału w klasycznym złożu PFB oraz 99,4% zmienności wyjaśnionej w odmianie fontannowej.

Słowa kluczowe: suszarka pulsofluidyzacyjna, kinetyka suszenia, suszenie fluidalne

1. Introduction

Pulsed fluid bed dryer technique relies on passing air through a layer of dried material with the stream directed at parts of a sieve tray instead of the entire surface of the screen as performed in the case of a fluid bed drying system. The stream of air is moved sequentially between the sections of a sieve tray chamber. Moving air flow between sections causes a cut-off of the drying air to the section and, consequently, loss of heat supply to the dried material in a given section. Preliminary studies of the drying kinetics carried out on mustard seeds indicated a minimal difference in the rate of drying between fluidized and pulsed fluid bed methods used in the procedures [5]. The results suggest that significant savings in energy can be obtained with only slight differences in the time of seed drying.

Operation of fluidized bed dryers and the kinetics of drying of cereals in fluidized bed systems are widely described in the literature. Research is carried out into the use of energy from different sources (classic heating by air drying [6, 7] and / or use of microwave energy [9]) and innovation design solutions in drying apparatus for improving the efficiency of drying process, ultimately leading to energy saving and improving the quality of dried material. The use and operation of a fluid bed dryer results in high process costs due to the excess air to be pumped through the drying chamber as compared to the amount of moisture being removed. One of the many methods of cost reduction of the process may be through the use of pulsed fluid bed drying techniques [3]. Hydrodynamics studies of pulse fluid bed showed that the range of gas velocities used in the pulsed

fluid bed dryer of cyclically relocated gas stream, contained between the lower and the upper pulsed fluidization velocity, is significantly below the working range used in systems employing fluidized beds for the same materials. Moreover the whole working velocity range (between lower and upper pulsed fluidization velocity) exhibits tendency to decrease in response to the growth in the equivalent diameter of seeds [15]. Other studies have shown that it is possible to obtain a 25-30% saving in the demand for air and, correspondingly, for the energy consumption [5].

Drying kinetics of wheat, barley and rapeseed in classic pulsed bed fluid dryers has already been developed [3]. The kinetics of drying grain seeds described by a model equation is shown in Table 1.

A novel solution regarding construction of fluidized bed dryers is the use of a variable cross-section of the drying chamber in the space above the screen where the drying chamber is shaped as a fountain. This solution is widely used because of good conditions for mixing the dried material. Studies on drying rice and wheat [6] showed that in comparison to the classic fluidized bed system layout, fountain-shaped chamber shows a superior energy utilization based on the amount of evaporated moisture and, consequently, higher maintenance of germination of rice and wheat seeds after drying at higher temperatures. The articles suggests that seeds dried in a fountain-shaped chamber at high gas temperatures exhibited slightly better germination properties than the seeds dried in a classic chamber, property most likely connected to the intermittent heat supply to kernels.

Table 1. List of models used to describe the kinetics of corn drying
 Tab. 1. Modele zastosowane do opisu kinetyki suszenia kukurydzy

Pos.	Model	Model equation	Ref.
(3)	Lewis	$X_{red} = \exp(-k \cdot t)$	1, 8, 9
(4)	Page	$X_{red} = \exp(-k \cdot t^N)$	1, 8, 9, 12, 13
(5)	Henderson, Pabis	$X_{red} = A \exp(-k \cdot t)$	1, 8, 9, 14
(6)	Two compartment model	$X_{red} = A \exp(-k_1 \cdot t) + B \exp(-k_2 \cdot t)$	9
(7)	Glaser Gawrzyński	$X_{red} = \exp(-k \cdot t^N \cdot T_g^B)$	3
(8)	Page's modified	$X_{red} = \exp\left(-k \cdot t^N \cdot \exp\left(-\frac{B}{T_g}\right)\right)$	9

Source: own work / Źródło: opracowanie własne

The current article discusses applicability of use of a classic or a spouted chamber for drying corn. A spouted variety of pulsed fluid bed system was not used for drying seeds or other particulate materials despite many advantages of pulsed fluid bed drying chambers. Corn was selected as a test material, based on the fact that its production in Poland reached nearly 4 million tons in 2012, making it one of the most important cereals [2].

2. Materials and Methods

2.1. Materials

Maize hybrid P8400 (suitable for growing grain) belonged to a medium early group based on the FAO 24 number. The equivalent diameter of the material was $d_p = 8.36$ mm. Bulk density of the wet corn (for moisture content $u = 27\%$) was 674.4 kg/m^3 and 623.7 kg/m^3 for dry maize (moisture content $u = 13\%$). Studies utilizing classic pulsed fluid bed dryer (PFB) were conducted on fresh corn with an average seed moisture content of 25.4%. Drying of seeds in a spouted pulsed fluid bed dryer was performed on rewetted corn. Seeds were pre-dried to a moisture content of 20% at the drying gas temperature of 35°C, sprinkled on a heap and stored at 14°C and 50% relative humidity. After storage, the seed moisture content was 16%. For the measurements, seeds were rewetted by adding a calculated amount of distilled water and stored at 4°C for 12h. The average moisture content of corn before drying was 25.9%. The process was conducted in order to adjust the grain humidity to approx. 12%.

2.2. Experiments

The study was performed in a classic pulsed fluid bed dryer (PFB) [11] and in a spouted pulsed fluid bed dryer (SPFB) [10]. Dryers are shown in Fig. 1. The dimension of sieve trays in a PFB dryer was 0.12 x 0.60 m and 0.03 x 0.60 m in a SPFB dryer. Height of the spouted part in the spouted chamber was 0.45 m. Chamber of the dryer was divided horizontally into two parts by a sieve tray. Part above the tray constituted the drying chamber while the part under the tray was divided into pressure chambers. An integral part of the apparatus was a gas distributor equipped with a rotary disc. The distributor had a gas inlet and several outlets. Each outlet from the manifold pipe was connected to the chamber providing thrust. The number of outlets of the distributor was equal to the number of pressure chambers. The disc in the gas distributor had one opening directing the flow of drying gas into the drying chamber through an opening in the shield, the pressure chambers,

sieve tray sections and above the sieve tray to contact directly the dried material. Rotation of the distributor disc split the gas stream for subsequent discharge through openings. The openings were connected by pipes to pressure chambers located under the tray in the body of the dryer. In this way, forwarding the gas stream to subsequent openings directs gas stream to subsequent gas distributor outlets and thus to the subsequent pressure chamber sections and sieve trays. In this way, each pressure chamber has an interrupted gas flow supply. The intermittent nature of the gas flow through the pressure chamber leads to an intermittent gas flow into the drying chamber and thus an intermittent contact with the drying material. Instantaneous gas velocity in the drying chamber could change from 0 to a maximum value w_{max} [4].

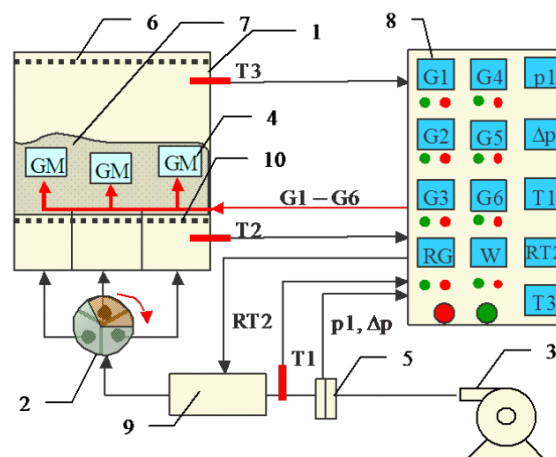


Fig. 1. Experimental set-up [14]: 1- Main chamber, 2- Gas distributor, 3- Fan, 4- Microwave generator, 5- Gas flow meter, 6- Microwave security unit, 7- Dried material, 8- Console, 9- Gas heater, 10- Supporting grid, T1, T2, T3 - Thermometers

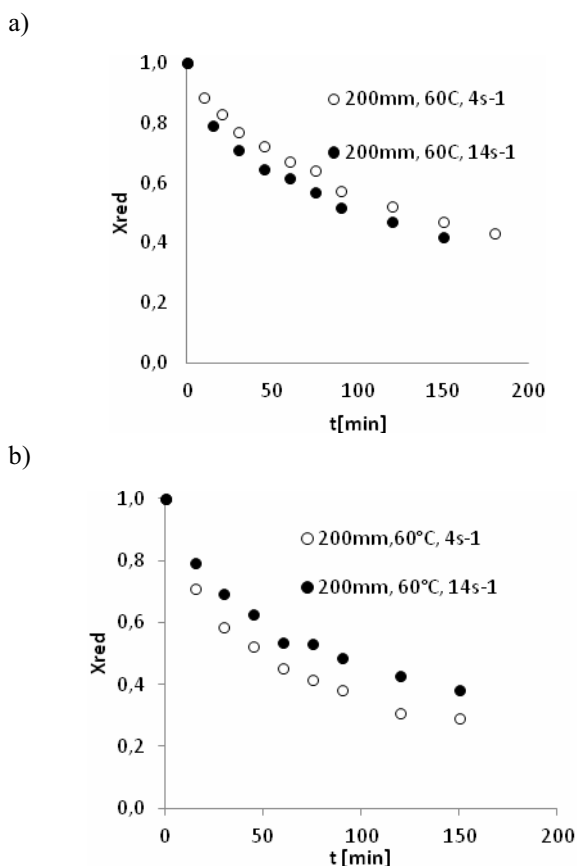
Rys. 1. Stanowisko pomiarowe [14]

2.3. Parameters ranges

The tests were performed within the process temperature of 50-70°C. Study in both systems was carried out on a static bed height 100-200 mm, with the frequency of disc rotation in the range 4-14s⁻¹. Single load of corn into the drying chamber of the dryer was 4kg with the bed height set at 100 mm and 8kg for the bed height of 200 mm for the PFB system. In the SPFB system, the corresponding corn loads were 1.8 kg and 4.2 kg.

3. Results and Discussion

Experimental results confirmed dependence of drying kinetics on the drying gas temperature. There was a strong correlation of the drying time with the temperature of the drying gas. Increasing gas temperature from 50°C to 60°C resulted in shortening of drying time from 240 to 150 minutes. Also, lowering the height of the bed reduced the drying time. Lowering the bed height from 200 mm to 100 mm reduced the drying time by approximately 30min. The shape of the drying chamber in the spouted dryer caused the mass of material in the layer at height $H_0 = 100$ mm to be less than half the mass of material in the same layer in a classic pulsed fluid bed dryer. Experimental results did not show significant differences in the kinetics of corn drying between the two systems for the same total weight of material in the chamber. However, experiments showed a significant difference in drying kinetics of corn depending on the frequency of distributor disc rotation for both systems. In a classic system, it was preferable to increase the frequency of disc rotation in order to have higher drying rates while the opposite was observed in the spouted bed system (Figure 2b). The frequency of rotation of the distributor disc affected mixing conditions of drying material in the pulsed fluid bed system.



Source: own work / Źródło: opracowanie własne

Fig. 2. Dependence of corn drying curves on the frequency of the disc rotation for gas distributor in the a) classic pulsed fluid system and b) spouted pulsed fluid system
Rys. 2. Zależność krzywych suszenia kukurydzy od częstotliwości obrotu tarczy rozdzielacza gazu a) w układzie klasycznym pulsofluidalnym, b) w fontannowym układzie pulsofluidalnym

4. Modeling of drying kinetics in pulsed fluid bed dryers

To describe the kinetics of drying corn, models presented in Table 2 were used. These models describe the relationship between the reduced moisture content and the drying time by an exponential or exponential-like function. Reduced humidity is described by formula (Eq. 1):

$$X_{red} = \frac{X - X_e}{X_0 - X_e} \quad (1)$$

The equilibrium moisture content was determined from the formula [7] (Eq. 2).

$$X_e = \frac{1}{100} \left[\frac{\ln(1 - RH)}{-3,074 \cdot 10^{-5}(T + 273,15)} \right]^{1,8156} \quad (2)$$

where:

X - moisture content at the time [kg H₂O/kg of dry matter],
X₀ - initial moisture content [kg H₂O/ kg of dry matter],
X_e - equilibrium moisture content [kg H₂O/ kg of dry matter],
RH - relative air humidity [-], T - gas temperature [°C].

These are semi-empirical models often used to describe the kinetics of convective drying of agriculture and food materials [1, 6, 7, 13] and microwave assisted drying [9]. Stanislawski applied the model of Henderson, Pabis to describe the drying kinetics of microwave assisted drying of carrots in a classic pulsed fluid drying bed chamber [13]. Although there were models of a thin film that did not take into account height of the bed, they were used successfully to describe kinetics of corn drying in a classic and a spouted fluidized beds with heights of 0.1 m and 2.4 m, respectively [6, 7] and about 0.2 m [14].

Research by Jittanit et al. [6] suggested that for drying corn, rice and wheat in a fluidized bed dryer the best fit of model to experimental results was obtained with the modified model of Page (tests were performed in a fluid bed dryer with dimensions close to the dimensions of the PFB dryer). The best fit and model test results for a spouted bed dryer were obtained for drying rice and wheat using a two-compartment model, later modified to obtain a better fit to the experimental results. Studies of seed drying kinetics in a pulsed fluid bed dryer were performed for wheat, barley, rape, carrots and beets [3]. Gawrzynski and Glaser's model [3] modified the Page's model by introduction gas temperature into the equation, a parameter considered to be the most significant in the kinetics of drying.

To determine the coefficients in model equations, non-linear regression models were used according to the Levenberg-Marquardt algorithm available in the Statistica 10 software. The determined coefficients and correlation coefficients R² and the root mean square (RMS) are given in Table 3. In general, the higher correlation coefficient R² and the lower the RMS, the better is the fit to the model curves determined experimentally and the overall prediction of the process.

The parameters of equations were determined for all previously used models describing the kinetics of convective and convection microwave drying of particulate material. The data in Table 2 shows that the best curve fit of the model and the best experimental model were obtained for the Gawrzynski-Glaser model.

Table 2. List of model coefficients determined for the classic pulsed fluid bed dryer over a range of $100 < H_0 < 200$ mm, $4 < f < 14 s^{-1}$ and $50 < T_g < 70^\circ C$

Tab. 2. Współczynniki w równaniach modelowych dla klasycznego układu pulsofluidalnego w zakresie parametrów $100 < H_0 < 200$ mm, $4 < f < 14 s^{-1}$, $50 < T_g < 70^\circ C$

Model	A	k	N	B	R ²	MRS
Lewis	-----	0,006562	-----	-----	88,94	0,6245
Henderson and Pabis	0,9088	0,00538	-----	-----	91,58	0,4824
Page	-----	0,034343	0,64047	-----	94,55	0,3167
Page modified	-----	32,79	0,707	2370,86	96,64	0,1974
Gawrzynski and Glaser	-----	0,00014	0,7079	1,2855	96,73	0,1921
	A	k ₁	B	k ₂		
Two compartment	0,4762	0,02111	0,5207	0,00166	95,05	0,2889
	k	N	B	C	D	
Gawrzynski and Glaser modified	0,00089	0,69601	0,8229	-0,0590	0,16485	97,61

Source: own work / Źródło: opracowanie własne

Table 3. Equation coefficients determined for the model used for spouted pulsed fluid bed dryer over a parameter range of $100 < H_0 < 200$ mm, $4 < f < 14 s^{-1}$ and $50 < T_g < 60^\circ C$

Tab. 3. Współczynniki w równaniach modelowych dla fontannowego układu pulsofluidalnego w zakresie parametrów $100 < H_0 < 200$ mm, $4 < f < 14 s^{-1}$, $50 < T_g < 60^\circ C$

Model	A	k	N	B	R ²	MRS
Lewisa	-----	0,0119	-----	-----	90,72	0,32352
Henderson and Pabis	0,87389	0,00889	-----	-----	93,90	0,21615
Page	-----	0,07792	0,5511	-----	98,67	0,04810
Page modified	-----	0,7201	0,5612	748,702	98,77	0,04444
Gawrzynski and Glaser	-----	0,00009	0,9929	1,1859	99,20	0,04496
	A	k ₁	B	k ₂		
Two compartment	0,44178	0,04659	0,55270	0,00405	98,66	0,04867
	k	N	B	C	D	
Gawrzynski and Glaser modified	0,0308	0,5797	0,46589	-0,1318	-0,1546	99,44

Source: own work / Źródło: opracowanie własne

Modifications to the Gawrzynski-Glaser model were suggested, by introduction into the equation other variables having influence on the drying kinetics of particulate material in the pulsed fluid bed dryer: bed height H_0 [mm] and the frequency f [s^{-1}] of disc rotation in the distributor (Eq. 9).

$$X_{red} = \exp(-k \cdot t^N \cdot T_g^B \cdot H_0^C \cdot f^D), \quad (3)$$

where:

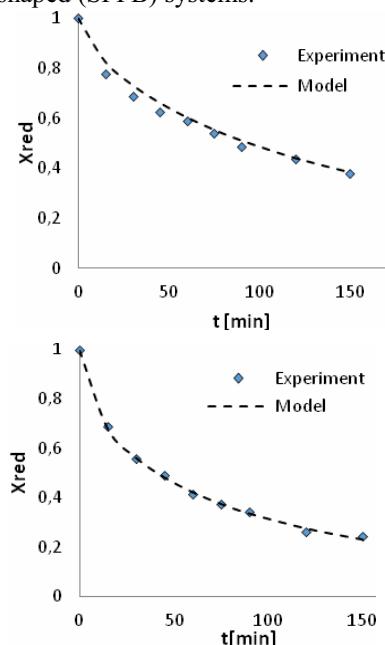
H_0 - height of the static bed [mm],

f - the frequency of rotation of the disc distributor [s^{-1}] and

k, N, B, C, D - constants.

Parameter calculations were performed for corn dried in conventional and spouted pulsed fluid bed dryers according to the model equations listed in Table 1 as well as the modified equation parameters. Table 2 lists the constants in the equations, the correlation coefficient R^2 and the root mean square (MRS). The table shows that the lowest value of the MRS and the highest regression coefficient were obtained for the new, modified form of the Gawrzynski-Glaser model. Modifications took into account variability of all the parameters measured for the system and the nature of the impact of individual variables on the drying kinetics. The model shows that increase of gas temperature and lowering of bed height had a beneficial effect on the drying time in both systems. The model also takes into account the nature of the negative influence of disc distributor rotation frequency on the kinetics of corn drying in both systems. Higher rotation frequencies are preferred in the PFB system while the opposite was observed for the SPFB system. Fig. 3 shows representative drying curves obtained from the

experiment and the model for the classic (PFB) and the fountain-shaped (SPFB) systems.



Source: own work / Źródło: opracowanie własne

Fig. 3. A representative drying curve obtained from experimental data and the fitted model for the a) classic (PFB) and b) spouted pulsed fluid bed (SPFB) systems

Rys. 3. Przykładowa krzywa suszenia uzyskana z eksperymentu i modelu a) dla klasycznego układu pulsofluidalnego (PFB) b) dla fontannowego układu pulsofluidalnego (SPFB)

5. Conclusions

Type of influence of the disc gas distributor rotation frequency on corn seeds drying kinetics in a pulsed fluid bed dryer system depends on the dryer design. In a classic PFB system, it is preferred, from the point of view of drying time shortening, to use high frequency of disc rotation while the opposite is true for the fountain-shaped SPFB system.

A new form of a model equation describing drying of granular materials was introduced which took into account all the variables of the pulsed fluid bed dryer system. The best curve fit of the model to the experimental data was obtained for both the classic and the spouted system.

Corn drying curves for the same weight of dried material in the drying chamber for the classic and spouted pulsed fluid dryers do not show significant differences. Choosing the right variety of dryers for coarse material may depend on other factors, e.g. energy consumption based on the amount of moisture removed or the seed quality measured by the amount of germinating grains.

6. References

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