Drying peppercorn characteristics in fluidized bed dryer equipped with baffle vortex generators

To cite this article: V Chuwattanakul et al 2018 IOP Conf. Ser.: Earth Environ. Sci. 136 012020

View the article online for updates and enhancements.

You may also like

- Drying and breaking behavior of hot air heavy medium fluidized bed Lingyue Li, Jiangjiang Qu, Shenglun Zhou et al.
- Drying process of black pepper in a swirling fluidized bed dryer using experimental method N F M Roslan and A S M Yudin
- Effect of Vibrating Fluidized Bed (VFBD) and continuous microwave drying on drying characteristic of green tea S U Handayani, M E Yulianto, S Sutrisno et al.
Drying peppercorn characteristics in fluidized bed dryer equipped with baffle vortex generators

V Chuwattanakul¹, K Banthumporn¹, P Promvonge¹ and S Eiamsa-ard²

¹Faculty of Engineering, King Mongkut’s Institute of Technology Ladkrabang, Bangkok 10520, Thailand
²Faculty of Engineering, Mahanakorn University of Technology, Bangkok 10530, Thailand

E-mail: varesaatkmitl@gmail.com

Abstract. The paper deals with the characteristic study of drying peppercorn using fluidized-bed dryer fitted with baffle vortex generators. The experiments were operated at three different superficial air velocities of 1.2Umf, 1.4Umf and 1.6Umf. Experiments were operated from the initial to final moisture contents of around 12% (dry basis). During the experiments, peppercorns were sampling every 5 minutes, for moisture analysis. A typical fluidized-bed dryer was also tested under similar operating conditions for the assessment. The results indicate that the influence of superficial air velocity on drying peppercorn characteristic in the fluidized-bed dryer fitted with baffle vortex generators is more significant than that in the typical fluidized-bed dryer. It is observed that fluidized-bed dryer fitted with baffle vortex generators shows better performance in reducing moisture content with faster drying rate than the typical fluidized bed dryer especially at high superficial air velocity due to the strong longitudinal vortex which helps in improving the fluid mixing, heat and mass transfer rates.

1. Introduction
Peppercorn is one of economical crops in Thailand which gives export income of around 50-70 million baht per year. The average capacity of peppercorn production is 3.5 million tons per year. Peppercorn was used not only herbal ingredient in various kind of foods but also used as food additive and flavour. It contains essential volatile oils that assist to preserve food and extend shelf life. Drying of foodstuff is one of popular thermal processes that help to preserve foods by removing of water. This process helps to inhibit growth of bacteria, yeasts, and mold that cause food deterioration. Drying process is simultaneous heat and mass transfer. During the process, heat is supplied to particle of material and moisture vapor is removed from the material into drying medium. Although there are various ways of drying method for food preservation, fluidized-bed drying is a one of promising alternative technique which is fast, easy, less time and homogenous drying used for small food products.

Drying kinetic behaviors in the drying of different food products have been extensively reported. Kooli et al. [1] investigated drying behaviors such as moisture content (MC) and drying rate of the red pepper at different test conditions (greenhouse and open sun). Scala et al. [2] proposed the mathematical model for predicting the drying rate of red pepper. In addition, the product results (nutritional and organoleptic attributes) was also reported. Darvishi et al. [3] investigated the effect of microwave power on the drying kinetics, energy consumption and drying efficiency of green pepper during different microwave drying. They found that the drying time decreased from 9 to 2.5 min,
attributed to the promoted moisture diffusivity by increasing the microwave output power from 180 to 540 W. Łechtańska *et al.* [4] presented the drying characteristics (drying kinetics, product quality and energy consumption) of green pepper with hybrid drying between convective drying and microwave drying. Azaizia *et al.* [5] modeled a new solar greenhouse drying system for the drying of red peppers. They proposed mixed-mode (SGDS) consisted of two parts (flat plate solar air collector and greenhouse). The effects of the area of the product to be dried, airflow rate and collector area, on moisture content changes, air temperature and humidity inside the greenhouse were also reported. According to the literature review, the drying efficiency is strongly dependent on drying method and condition. From the previous works, vortex generators have been used for enhancing the heat transfer rate in thermal systems [6-16]. This research aimed to further improve the drying efficiency of the conventional fluidized-bed dryer (FBD) by equipping baffle vortex generator with the dryer. For an assessment, the conventional/typical fluidized-bed dryer without baffle vortex generator was also tested. Peppercorns were used as the drying feed. In each operating run, 400 grams of fresh peppercorns with the initial moisture content at about 550% (wet basis) were dried using hot air with constant temperature. The inlet hot air temperature was 70°C, the relative air humidity 63% and the air velocity varied from about 1.2Umf to 1.6Umf. Furthermore, five mathematical models (Newton/Page/Modified-Page/Logarithmic/Henderson and Pabis) are applied in terms of moisture ratio (MR) with respect to drying times (DT).

2. Theoretical analysis
In the present work, the model is presented the relationship between moisture and drying time by means of regression analysis [17-18] as found details in table 1. The moisture ratio (MR) is usually expressed as.

\[
MR = (M - M_0)/(M_0 - M_e) \tag{1}
\]

The drying speed or drying rate of samples is expressed as

\[
DR = dM/dt = (M_{t,+} - M_{t-})/dt \tag{2}
\]

To evaluate the fitting process of each mathematical model, (1) correlation coefficient (R²), (2) root mean square error (RMSE) and (3) chi-square (χ²) were considered. The regression analysis was performed by using statistical software. The best fitting model is the one giving the highest of correlation coefficient (R²) and the lowest root mean square error (RMSE) and chi-square (χ²). Details of the statistical package based are presented in equation below and table 1.

\[
RMSE = \left[\frac{1}{N} \sum_{i=1}^{N} (MR_{\exp,i} - MR_{\text{pred},i})^2 \right]^{1/2} \tag{3}
\]

and

\[
\chi^2 = \frac{\sum_{i=1}^{N} (MR_{\exp,i} - MR_{\text{pred},i})^2}{N - p} \tag{4}
\]

Table 1. Mathematical models applied to the drying curves.

| Model name            | Model                  | References               |
|-----------------------|------------------------|--------------------------|
| Page                  | MR = exp(-kt^a)        | Doymaz and Pala [19]     |
| Modified Page         | MR = exp(-(kt)^b)      | Zhang and Litchfield [20]|
| Newton                | MR = exp (-kt)         | Ayensu [21]              |
| Henderson and Pabis   | MR = a exp (-kt)       | Henderson and Pabis [22]  |
| Logarithmic           | MR = a exp(-kt)+c      | Kassem [23]              |

3. Experimental description
Peppercorn is one of economical crops in Thailand which gives export income of around 50-70 million baht per year. The average capacity of peppercorn production is 3.5 million tons per year. Peppercorn was used not only herbal ingredient in various kind of foods but also used as food additive and flavour. It contains essential volatile oils that assist to preserve food and extend shelf life. Drying of foodstuffs is one of popular thermal processes that help to preserve foods by removing of water. This process helps to inhibit growth of bacteria, yeasts, and mold that cause food deterioration. Drying process is simultaneous heat and mass transfer. During the process, heat is supplied to particles of material and moisture vapor is removed from the material into drying medium. Although there are various ways of drying method for food preservation, fluidized-bed drying is a one of promising alternative technique which is fast, easy, less time and homogenous drying used for small food products.

3.1. Materials
Fresh green peppers were harvested from a green house in the Chanthaburi province of Thailand, in March 2017 and were stored in the refrigerator at temperature of 4 °C until the experiments were carried out. Before the experiments, the samples were removed from the refrigerator and allowed to reach room temperature (about 25 °C). The green peppers (average dimensions of 4.5± 0.1 mm diameter) were washed and halved as seen in Fig. 1. It was selected carefully in an attempt to minimum effect of the kernel size. The green pepper had an initial moisture content of 550% (wet basis), which was determined by drying in a convective oven at 105 °C until the weight became constant.

![Figure 1. Photograph of fresh peppercorns.](image)

3.2. Experimental setup and method
The fluidized bed dryer with vortex generators was set up by equipping baffles with the typical fluidized-bed dryer. The baffle bundles used in the present experiment are also demonstrated in Fig. 2. The baffle vortex generators were made of stainless sheet with thickness of 1.2 mm. Each baffle is connected to the other in series with constant pitch lengths (P) of 210 mm which correspond to pitch ratios (P/D) of 1.5. The baffle bundles were inserted into the bed/column. It is noteworthy that the bed alone (typical fluidized-bed dryer) was also tested for comparison. The setup of the fluidized-bed dryer with baffle vortex generator was the same rig as the typical fluidized-bed dryer but different bed. The baffle was used to create vortex/recirculating flows or to increase the lateral fluidization in the bed apart from the vertical fluidization. A numerical simulation of the flow behaviours at superficial velocity of 1.2Umf in the fluidized-bed with baffle vortex generator is depicted in Fig. 2. It can be observed that two longitudinal vortex flows generated by the baffle bundles that could be helped to induce chaotic mixing between peppercorns and hot air leading to shorter drying time in comparison with the plain bed.

A schematic diagram of the experimental setup is shown in Fig. 3. The experimental facility consisted of bed column with/without baffle vortex generators (B-FBD/FBD), distributor plate, sample-containing bowl, weight digital, 5 kW electric air heater unit, 10 hp high pressure air blower, temperature controller, hot wire anemometer for calibrating, orifice flow meter with pressure different digital for measuring the volumetric air flow rate, power meter and an inverter. The bed made of acrylic cylinder with 140 mm in diameter and 1000 mm height. A perforated plate with 140 mm
diameter was located at the bed bottom as air distributor. The plate consisted of 408 holes, the diameter of each hole was 3 mm (total hole area was 75% of total plate area).

**Figure 2.** Streamlines displaying flow structure in B-FBD.

For fluidized bed drying, the most significant component is the drying column. Therefore, the thermal balance was derived by applying mass, energy and entropy balances to the drying column in batch fluidization. The drying process in a batch-fluidized bed was modeled by assuming a perfect mixing of
particles. The process took place under isobaric condition due to the simultaneous heat and mass transfer between hot air and peppercorns. The superficial air velocities in the bed were set to be $1.2U_{mf}$, $1.4U_{mf}$ and $1.6U_{mf}$, respectively. A blower supplied air through a 5 kW electric air heater unit. The blower speed could be adjusted via an inverter where the volumetric air flow rate was monitored by through an orifice flow meter. All hot air passages were wrapped by insulation to minimize heat loss to environment. The system was preheated until the rig temperature was constant at 70˚C before running the experiment. When the rig temperature was steady, the 400 grams of peppercorn feed was loaded into the rig. The corn grain was sampled every 5 minutes for moisture measuring. Drying was corrected until a moisture content (MC) of 10% (dry basis) or lower. After drying process, the peppercorns in the drying bed were removed and weighed by digital weighing scales which recorded to the personal computer (PC).

![Figure 4](image.png)

**Figure 4.** Relationship between moisture content (MC) and drying time (DT) of peppercorn at various superficial air velocity of fluidized-bed dryer fitted with/without baffle vortex generators.

![Figure 5](image.png)

**Figure 5.** Relationship between moisture ratio (MR) and drying time (DT) of peppercorn at various superficial air velocity of fluidized-bed dryer fitted with/without baffle vortex generators.
4. Results and discussion
In this experimental result sections, the influences of superficial air velocity (1.2U_{mf}, 1.4U_{mf} and 1.6U_{mf}) on drying behaviours of peppercorns are described regarding to the results in Figs. 4-8. Then, the comparison of drying in the typical fluidized-bed dryer and the fluidized-bed dryer fitted with baffle vortex generators are reported in Figs. 6-7. Evidently, the moisture content of peppercorns decreases with drying time for both in the typical fluidized-bed dryer (FBD) and the fluidized-bed dryer fitted with baffle vortex generators (B-FBD) as seen in Figs. 4 and 5. The moisture content (MC) of peppercorn abruptly decreases in the initial period and thereafter the moisture content (MC) gradually reduced during the mechanism of convection from the vaporization rate of heat and mass transfer between the peppercorns and hot air. At the same drying time (DT), the moisture content of peppercorns tends to decrease with increasing superficial air velocity. Because more available hot air as the carrier at higher superficial velocity, thus moisture can be removed more efficiently. It is noteworthy that the influence of superficial air velocity on drying peppercorn in the fluidized-bed
dryer fitted with baffle vortex generators (B-FBD) is more significant than that in the typical fluidized-bed dryer (FBD). The more significant outcome in the dryer with baffle vortex generators can be attributed to the combined effects of vortex flow with the increased axial flow.

![Figure 8](image.png)

Figure 8. Relationship between drying rate (DR) and moisture content of peppercorn at various superficial air velocity of fluidized-bed dryer fitted with/without baffle vortex generators.

![Figure 9](image.png)

Figure 9. Comparison between experimental and predicted data of FBD fitted with/without baffles of all superficial air velocities (1.2Umf, 1.4Umf and 1.6Umf).

The comparison in Fig. 4 shows that at the same drying time, the moisture contents (MC) of peppercorns in the fluidized-bed dryer fitted with baffle vortex generators of all superficial air velocity (1.2Umf, 1.4Umf and 1.6Umf) are considerably lower than those in the typical fluidized-bed dryer. In
other words, the drying efficiencies or drying rates in the fluidized-bed dryer fitted with baffle vortex generators are higher than those in the typical fluidized-bed dryer. The better performance of the one with baffle vortex generators is due to the higher turbulence intensity which leads to better contact leading between the hot air and the peppercorns (gas-particle) and thus higher water evaporation due to high heat and mass transfer rate with smaller flow area.

The results in Fig. 6 also indicated that all drying curve consist of two stages: (1) constant rate period and (2) falling rate period. Interestingly, the constant rate period in the typical fluidized-bed dryer fitted with baffle vortex generators (B-FBD) ends within the first 100 minutes while that in the typical fluidized-bed dryer (FBD) extends until around 80 minutes. The shorter constant rate period in the fluidized-bed dryer fitted with baffle vortex generators (B-FBD) is attributed to the lower remaining moisture content of peppercorns due to the faster drying or higher moisture diffusion in the constant rate period.

Influence of the bed fitted with baffle vortex generators and superficial air velocity (1.2Umf, 1.4Umf and 1.6Umf) on drying rate (DR) is also examined and presented in Fig. 6. It is obvious that the drying rate (DR) is decreased continuously with increasing drying time (DT) which it is no constant rate period in the drying curve of present drying rate. It is also found that the drying rate (DR) tends to decrease with raising the drying time (DT) as mention above and the fluidized-bed dryer fitted with baffle vortex generators (B-FBD) gives the drying rate (DR) higher than the typical fluidized-bed dryer (FBD) for all superficial air velocity. At the beginning drying process or drying time, the drying rate (DR) of the fluidized-bed dryer fitted with baffle vortex generators (B-FBD) is visible to be high than that typical fluidized-bed dryer (FBD) due to strong longitudinal vortex flow performs rise to higher turbulence intensity between the hot air and the peppercorn grains in the bed. This implies that the use of fluidized-bed dryer fitted with baffles with high superficial air velocity leads to higher heat and mass at the beginning of drying process due to very high moisture content in fresh peppercorns. The initial values (0-25 minutes) of drying rate (DR) for the fluidized-bed dryer fitted with baffle vortex generators and the typical fluidized-bed dryer are, respectively, about 57% and 31% at the superficial air velocity of 1.6Umf, and it becomes less important after approximately 25 minutes for the fluidized-bed dryer fitted with baffles but the typical fluidized-bed dryer is different since the change of the drying rate (DR) is nearly constant for longer drying time. The highest drying rates (DR) of the fluidized-bed dryer fitted with baffles at superficial air velocity of 1.2Umf, 1.4Umf and 1.6Umf are up to 16%, 47% and 58% higher than that typical fluidized-bed dryer in the range of drying time of 0-15 minutes.

Relationship between the drying rate (DR) and moisture content (MC) or moisture ratio (MR) is presented in Figs. 7 and 8. It is clearly seen that the drying rate (DR) is varied linearly with those the moisture content (MC) and moisture ratio (MR) and also seen that at higher superficial air velocity (Umf) the slope became steeper than the lower superficial air velocity (1.2Umf and 1.4Umf), especially for the fluidized-bed dryer fitted with baffle vortex generators which it is also found that the drying rate (DR) is decreased with the reduction of moisture content (MC) and moisture ratio (MR). The drying rate (DR) of the fluidized-bed dryer fitted with baffles are higher than those of typical fluidized-bed dryer for all superficial air velocity. In addition, the average drying rate (DR) of the fluidized-bed dryer fitted with baffles are, respectively, seen to be around 2.83, 1.91, and 2.69 g water/min for superficial air velocity of 1.2Umf, 1.4Umf and 1.6Umf in the range of drying time of 0-25 minutes.

For mathematical modelling, the moisture content of peppercorns at different drying velocities (superficial air velocities of 1.2Umf, 1.4Umf and 1.6Umf) obtained from the experiment data are predicted with five different mathematical models for example the Newton model, Page model, Modified Page model, Henderson and Pabis model, and Logarithmic model in the form of the moisture ratio (MR) as demonstrated in Table 1 and Fig. 9. In the present study, the modelling works were done using least square algorithm in MATLAB at various superficial air velocities. Table 2 and Fig. 9 presented the comparison criteria used to evaluate the RMSE, chi-square ($\chi^2$) and $R^2$. A comparison of the present experimental data versus the predictions (from five different models) of statistical parameter examines (RMSE, $\chi^2$ and $R^2$) for the for the drying peppercorn by using...
fl uidized-bed dryer fitted with baffle vortex generators with three superficial air velocities of \( I.2U_{mf} \), \( 1.4U_{mf} \) and \( 1.6U_{mf} \) is also displayed in Figs. 9 and 10.

**Table 2.** Statistical results for five mathematical models at various superficial air velocity (\( 1.2U_{mf} \), \( 1.4U_{mf} \) and \( 1.6U_{mf} \)) in term of \( U^* = U/U_{mf} \).

| Model               | \( R^2 \)   | RMSE       | \( \chi^2 \) |
|---------------------|-------------|------------|--------------|
| **FBD**             |             |            |              |
| Newton              | 0.9955892   | 0.023295   | 0.0011305    |
| Page                | 0.9941618   | 0.0195168  | 0.0007936    |
| Modified Page       | 0.9693263   | 0.3204202  | 0.106947     |
| Henderson and Pabis | 0.995545    | 0.0230804  | 0.0028944    |
| Logarithmic         | 0.9978796   | 0.0105659  | 0.0001163    |
| **B-FBD**           |             |            |              |
| Newton              | 0.9993927   | 0.0034642  | 1.25E-05     |
| Page                | 0.9994227   | 0.0028532  | 8.48E-06     |
| Modified Page       | 0.99948     | 0.0029674  | 9.17E-06     |
| Henderson and Pabis | 0.9994917   | 0.0028033  | 8.72E-06     |
| Logarithmic         | 0.9995071   | 0.0011063  | 8.19E-06     |

It can be obvious that the predicted results of all models performed generally are in good agreement with the those the experimental work. It is also obvious that of all the mathematical models (Newton model, Page model, Modified Page model, Henderson and Pabis model, and Logarithmic model), the \( R^2 \), RMSE and \( \chi^2 \) value are ranged of 0.9693263 to 0.9978796, 0.0105659 to 0.3204202 and 0.0001163 to 0.106947 for the typical fluidized-bed dryer (FBD), and 0.9993927 to 0.9995071, 0.0011063 to 0.0034642 and 0.00000819 to 0.0000125 for the fluidized-bed dryer fitted with baffle vortex generators (B-FBD), respectively. Logarithmic model gives best due to the highest value of \( R^2 \) (0.9995071) and the lowest of RMSE (0.0011063) and \( \chi^2 \) (0.00000819). This means that the Logarithmic model gives the best fit with the measurement data as seen in the table 2 and Figs. 9 and 10. In addition, it is also clearly observed that at the low superficial air velocities (\( I.2U_{mf} \) and \( 1.4U_{mf} \)) of typical fluidized-bed dryer (FBD), use of the Logarithmic model leads to more accurate results than those other models in compared with the present data (measurement).
5. Conclusion

The drying characteristics of fluidized-bed dryer fitted with baffle vortex generators are experimentally investigated at various superficial air velocity. The main results from the present work can be summarized as follow below.

- The influence of superficial air velocity on drying peppercorn characteristic in the fluidized-bed dryer fitted with baffle vortex generators (B-FBD) is more significant than that the typical fluidized-bed dryer (FBD) at the initial interval of the drying time.
- The drying rate (DR) of fluidized-bed dryer fitted with baffle vortex generators (B-FBD) is dependent on superficial air velocities due to strong of dual longitudinal vortex near around the baffles that help to better the hot air mixing with the peppercorn leading to the higher mechanism of heat and mass transfer.
- The present drying rate data of the pepper corn of both dryer techniques were made to fit with five mathematical models which the best fit was based on the highest value of $R^2$, and lowest value of RMSE and $\chi^2$. Logarithmic model is performed the best fit model with the highest value of $R^2$ and the lowest value of RMSE and $\chi^2$ for B-FBD. Furthermore, B-FBD and FBD are compact and have good control over drying conditioned, relatively high drying rates at the initial interval of the drying time.

6. Acknowledgment

The authors would like to acknowledge with appreciation King Mongkut’s Institute of Technology Ladkrabang, Thailand for financial support of this work (KREF 015910).

7. Nomenclatures

- DR: drying rate (g water/min)
- MC: moisture content (%db)
- MR: moisture ratio
- M: moisture content any time (g water/g dry matter)
- Me: equilibrium moisture content (g water/g dry matter)
- M0: initial moisture content (g water/g dry matter)
- Mt: moisture content at t (g water/g dry matter)
Mt + Δt  moisture content at t + dt (g water/g dry matter)
t drying time (min)

8. References
[1] Kooli S, Fadhel A, Farhat A and Belghith A 2007 *J. Food Engineering* 79 1094
[2] Scala K D and Crapiste G 2008 *LWT-Food Science and Technology* 41 789
[3] Darvishi H, Asl A R, Asghari A, Azadbakht M, Najafi G and Khodaei J 2014 *J. Saudi Society of Agricultural Sciences* 13 130
[4] Łechtańska J M, Szadzińska J and Kowalski S J 2015 *Chemical Engineering and Processing: Process Intensification* 98 155
[5] Azaizia Z, Kooli S, Elkhadraoui A, Hamdi I and Guizani A A 2017 *Int. J. Hydrogen Energy* 42 8818
[6] Thianpong C, Eiamsa-ard P, Promvonge P and Eiamsa-ard S 2012 *Energy Procedia* 14 1117
[7] Eiamsa-ard S, Somkleeang P, Nuntadusit C and Thianpong C 2013 *Applied Thermal Engineering* 54 289
[8] Kongkaitpaiboon V, Nanan K and Eiamsa-ard S 2010 *Int. Comm. in Heat and Mass Transfer* 37 560
[9] Zhang X, Liu Z and Liu W 2013 *Int. J. of Heat and Mass Transfer* 60 490
[10] Thianpong C, Yongsiri K, Nanan K and Eiamsa-ard S 2012 *Int. Comm. in Heat and Mass Transfer* 39 861
[11] Matsunaga T and Sumitomo T 2014 *J. of Research and Applications in Mechanical Engineering* 2 65
[12] Eiamsa-ard S 2010 *Int. Comm. in Heat and Mass Transfer* 37 644
[13] Eiamsa-ard S, Wongcharee K and Promvonge P 2010 *Int. Comm. in Heat and Mass Transfer* 37 156
[14] Promvonge P and Eiamsa-ard S 2007 *Int. Comm. in Heat and Mass Transfer* 34 838
[15] Sivashanmugam P Nagarajan P K and Suresh S 2008 *Chemical Engineering Communication* 195 977
[16] Eiamsa-ard S Yongsiri K, Nanan K and Thianpong C 2012 *Chemical Engineering and Processing: Process Intensification* 60 42
[17] Yilbas B S, Hussain M M and Dincer I 2003 *Heat and Mass Transfer* 39 471
[18] Özdemir M and Devres Y O 1999 *J. of Food Engineering* 42 225
[19] Doymaz I and Pala M 2002 *J. of Food Engineering* 55 331
[20] Zhang Q and Litchfield J B 1991 *Drying Technology: An Int. J.* 9 383
[21] Ayensu A 1997 *Solar Energy* 59 121
[22] Henderson S M and Pabis S 1961 *J. of Agricultural Engineering Research* 6 169
[23] Kassem A 1998 *13th Int. congress on agricultural engineering* 6 (Morocco) February 2-6