Numerical investigation of air flow in a vertically paddy bed dryer using computational fluid dynamics

Weerachai Chaiworapuek¹, Nuttakorn Chuenboonma¹*, Teerapat Thungthong¹, Ratiporn Munprom², Sudathip Sae-tan³, and Damrongvudhi Onwimol⁴

¹Department of Mechanical Engineering, Faculty of Engineering, Kasetsart University, Bangkok Thailand 10900
²Department of Materials Engineering, Faculty of Engineering, Kasetsart University, Bangkok Thailand 10900
³Department of Food Science & Technology, Faculty of Agro-Industry, Kasetsart University, Bangkok Thailand 10900
⁴Department of Agronomy, Faculty of Agriculture, Kasetsart University, Bangkok Thailand 10900

* Corresponding Author: fengwcc@ku.ac.th

Abstract
This research focuses on the numerical investigation of air flow in a vertically paddy bed dryer using computational fluid dynamics - CFD. In this study, the Tubtim Chumphae paddy and perforated plates were assumed to be porous media and their properties were characterized experimentally in a 0.05 m × 0.05 m × 1 m duct. In this paper, the obtained porosity and permeability were applied to a numerical model, the air flow through a 100 kg paddy, stored in a vertical bed dryer. The results from the simulation and experiment agreed well with each other via the calibration process. The pressure drop across the dryer was found to increase when the inlet velocity gained from 0.025 to 0.1 m/s with an increment of 0.025 m/s. In this study, the results showed that air flow was controlled past the paddy with the deviation of less than 2.82% to achieve a high rice quality after the drying process. Because this drying technique used low temperature air and had low energy consumption, therefore, it is found to be one of the promising techniques and truly benefits the farmer in the future.

Keywords: CFD simulation, Bed grain drying, Energy, Paddy, Porous media

1. Introduction
In the last decade, more than 15,000 papers have been published to present experimental and mathematical models, which enhance the drying efficiency of grain dryers [1, 2]. Paddy is one of those grains, and it is the main food in many countries around the world [3]. After the paddy is harvested in rice fields, it has very high moisture content, so the drying process is needed before storage and milling operations. One of the simplest but effective dryers is the shallow-bed dryer, because the bed thickness is less than 20 cm. In this dryer, paddy depth does not affect the change of flow rate [4]. In industrial applications, paddy drying is an energy-intensive process, consuming specific primary energy between 1.44 and 74.73 MJ/kg. It could affect the odour and nutrition of paddy rice [5]. Meanwhile, the dryer
that operates using air with temperature below 40°C and flow rates less than 0.3 m³/s can preserve rice quality [6]. Following the advancement of numerical simulation, the computational fluid dynamics-CFD has been employed to investigate the flow in many applications including the air flow through the paddy [7-12]. The paddy is typically modelled as porous media, having porosity between 0.462 and 0.542 [13]. Mathematical modelling and simulation in 3D based on momentum and continuity equations with viscous resistance, inertial resistance and porosity of paddy porous zone are 10.626×10⁷, 18,605 and 0.57, respectively showed 10% error. This was studied under the case of 25 cm bed depth and air flow rate between 0.10 and 0.22 kg m⁻² s⁻¹ [14]. Some simulation results revealed that the shallow-bed dryer, having 4 ft bed height had a higher porosity when the bed height increased and humidity decreased [15]. The improvement of air distribution in a woodchip fixed-bed dryer, producing almost perfectly uniform air distribution could give the better performance for drying process [16]. Thus, this research focuses on the numerical investigation of air flow in a vertically paddy bed dryer using computational fluid dynamics – CFD to predict the uniformity of air flow that enters the paddy zone. The Tubtim Chumphae paddy and perforated plates, employed in the dryer were assumed to be porous media and their properties were characterized experimentally. The results obtained in this research would lead to the design of high performance vertical-bed dryer in the future.

2. Porous media investigations

2.1 Experimental setup
The permeability and porosity of Tubtim Chumphae paddy and 4 different types of perforated plate were investigated in the test section as depicted in Figure 1 to perform as porous media in the simulation. The test section had a size of 5 cm width × 5 cm height × 1 m length and the porous media was installed at the middle of the test section as depicted in the figure. For the paddy, the bed thickness (Δx) was 30 mm.

![Figure 1. Experimental setup for permeability and porosity measurement.](image)

For the test of perforate plate, the plate configurations were presented as shown in Table 1 and Figure 2. In the experiment of both paddy and perforated plate, the inlet velocity was set during 0.2 – 3 m/s, corresponding to the Reynolds number in the range of 340 – 10,300.

| Hole diameter (⌀) | Porosity (ε) | Hole pitch (p) | Thickness (Δx) |
|------------------|--------------|----------------|----------------|
| 5.0 mm           | 0.36         | 8.0 mm         | 1.0 mm         |
| 8.0 mm           | 0.77         | 12.0 mm        | 1.0 mm         |
| 9.5 mm           | 0.53         | 12.5 mm        | 1.5 mm         |
| 10.0 mm          | 0.47         | 14.0 mm        | 1.3 mm         |

![Table 1. The dimensions of perforate plate.](image)
2.2 Relating equations
For the calculation using computational fluid dynamics, the continuity and momentum equations are mutually utilized and they are as follows:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 (1)
\]

\[
\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) = -\nabla p + \mu \nabla^2 \mathbf{v} + \rho \mathbf{g} + \mathbf{F} (2)
\]

The fluid flow in porous media is modelled via a simple modification of the Navier-Stokes equations. The source term is added, responsible for an additional resistance or pressure drop to the flow exerted by the porous material in Equation 2. The source term of porous media was added as an external body force and the Darcy-Forchheimer equation or Equation 3 was employed. In the zone of porous media, the air flowed in one specific direction, shown as subscript i. Thus, the Darcy-Forchheimer equation can be described as follows:

\[
\Delta p/\Delta x_i = S_i = -\mu \cdot v_i / \alpha + 0.5 \cdot C_2 \cdot \rho \cdot |v| \cdot v_i (3)
\]

\[
\Delta p = av_i^2 + bv_i (4)
\]

\[
1/\alpha = b/(\mu \cdot \Delta x_i) (5)
\]

\[
C_2 = 2a/(\rho \Delta x_i) (6)
\]

Where \(1/\alpha, C_2\) and \(\Delta x_i\) represent the viscous resistance coefficient, inertial resistance coefficient and thickness of porous material, respectively.

3. Numerical method
In this paper, a validation process was conducted in the flow domain as the experiment, explained previously. It was a rectangular domain having 5 cm width × 5 cm height × 1 m length and the porous medias were set at the middle of the domain as depicted in Figure 3a. The permeability and porosity of porous medias were obtained from the experiment and the velocity inlet was set to be during 0.2 – 3 m/s as the experiment. The pressure difference obtained from the experiment and simulation would be compared to check the accuracy of numerical model. Then, a fixed-bed dryer was designed to have 2 vertical paddy beds and each had a cross-sectional area of 1.2 m × 0.6 m and a bed thickness of 0.2 m. The air domain inside the dryer is shown as Figure 3b. The inlet was set as velocity inlet of 1, 2, 3 and 4 m/s, corresponding to the velocity through the paddy of 0.025, 0.050, 0.075 and 0.100 m/s, respectively. The air from the inlet flowed pass 3 perforated plates and fins to decrease the turbulence and control the flow to have a uniformity of velocity distribution. A symmetry boundary condition was employed to reduce the computing resources and times. The mesh sensitivity method was conducted at the element number of 1,205,834, 2,899,632, 4,836,546, 6,905,562, 9,605,356 and 12,658,956. The pressure drop across the dryer was found to converge at the element number of 6,905,562 element model. Thus, this mesh size was selected and utilized through this study. Besides, the uniformity of air flows was checked by 2 standard deviation (2SD) and 2 relative standard deviation (2RSD) of air velocity on the paddy surface. The velocity on the paddy surface was sampling on the 4-vertical lines on the middle of each plenums of Z-axis coordinated at \(z = 0.125(150 \text{ mm}), 0.375(450 \text{ mm}), 0.625(750 \text{ mm})\) and 0.875(1,050 mm) from the bed width of 1,200 mm.
4. Results and discussion

4.1 Porous media properties and validation results
From the experiment, the properties of porous medias were measured as shown in Table 2. They were input to the numerical model as explained previously in the topic of validation process. The coefficient of determinations \(R^2\) between the pressure differences from experiment and simulation were obtained. The results showed that most cases except the case of a perforated plate with a diameter of 10 mm had the \(R^2\) above 0.95, confirming the accuracy of the numerical model. And, this model will be employed to predict the air flow in a dryer.

Table 2. Porous media properties and the \(R^2\) from validation process.

| Porous media          | Porosity | Permeability | Viscous resistance coefficient | Inertial resistance coefficient | \(R^2\) |
|-----------------------|----------|--------------|--------------------------------|---------------------------------|--------|
| Tubtim Chumphae paddy | 0.41     | 2.265×10^{-9} | 4.435×10^{-8}                  | 1884.0                          | 0.9956 |
| Perforate plate: \(\varnothing \) 5 mm | 0.36     | 5.965×10^{-7} | 1.677×10^{-6}                  | 11183.7                         | 0.9883 |
| Perforate plate: \(\varnothing \) 8 mm | 0.77     | 5.965×10^{-7} | 1.677×10^{-6}                  | 9575.5                          | 0.9687 |
| Perforate plate: \(\varnothing \) 9.5 mm | 0.53     | 8.947×10^{-7} | 1.118×10^{-6}                  | 3907.5                          | 0.9504 |
| Perforate plate: \(\varnothing \) 10 mm | 0.47     | 7.754×10^{-7} | 1.290×10^{-6}                  | 3579.3                          | 0.8865 |

4.2 Air flow results in a dryer
Figure 4a shows the air flow inside the dryer domain installing a perforated plate with 8 mm diameter when the velocity inlet is 4 m/s. The results present that the swirl flow appears at the entrance region and it decayed after passing 3 perforated plates. The velocity contour of air flow on the entering paddy surface was presented in Figure 4b. On this plane, the mean velocity was 0.112 m/s and 2 standard deviations is 0.0032 m/s or 2.825% for the case of the perforate plate with 8 mm diameter. This showed that the uniformity of velocity distribution performed at the entrance of the paddy chamber.
Figure 4. (a) Air path lines in the dryer (b) velocity contour at the entrance of paddy chamber.

Figure 5. Velocity profiles in the case of perforated plate with diameter of 8 mm and inlet velocity of (a) 0.1 m/s, (b) 0.075 m/s, (c) 0.05 m/s, and (d) 0.025 m/s.
The velocity profiles on the plane at the entrance of the paddy chamber are presented as shown in Figure 5. The results show that the velocity along the line of $z = 0.125, 0.375, 0.625, \text{ and } 0.875$ are in the same tendency, meaning that the velocity is quite uniform over paddy chamber. Only in region of $y = 0.5$, the profiles behave differently with other regions due to the separation flow from the horizontal fin before the air flow enters the paddy zone.

Moreover, the sizing effect of the hole diameter of perforated plate on the uniformity of air flow in dryer was also investigated. Figure 6 shows the velocity distribution error ($2\text{RSD}$) and pressure drop across the dryer ($\Delta P$) at 4 different hole diameters and 4 inlet velocities. The error as shown in Figure 6a gains with the increase in inlet velocity and it characterizes similarly when the diameter is 5 and 8 mm. Meanwhile, if the diameter is greater than 8 mm, the error is found to be increased when the hole diameter is bigger. The pressure loss as depicted in Figure 6b is slightly affected by the change in the hole diameter. Hence, the 8 mm diameter plate was recommended in attempt to employ in the dryer because it provided a uniformity of velocity distribution as the 5 mm diameter plate but it had a relatively lighter.

![Figure 6](image)

5. Conclusion
The uniformity of velocity distribution in a fixed-bed dryer, over the entry plane of paddy was investigated over 4 perforated plates, having different diameter size using computational fluid dynamics. The results showed that the 8 mm diameter model provided the relatively highest uniformity of velocity distribution with the error less than 2.82%. Besides, this paper also revealed the porous characteristics of Tubtim Chumphae paddy and perforated plate, having diameter of 5, 8, 9.5, and 10 mm. The obtained results in this research will offer key information for designing a vertical-bed dryer for paddy in the future.

Acknowledgments
The authors would to thank Kasetsart University, Bangkok, Thailand and National Research Council of Thailand-NRCT for financial support.

References
[1] Sivakumar R Saravanan R Perumal A and Iniyan S 2016 Renew. Sust. Energ. Rev. 61 280
[2] Tohidia M Sadeghib M and Harcheganic M 2017 Renew. Sust. Energ. Rev. 70 519
[3] Vaughan D Morishima H and Kadowaki K 2003 Curr. Opin. Plant Biol. 6-2 139
[4] Doungporrna S Poomsa-adb N and Wiset L 2012 Food Bioprod. Process 90-2 187
[5] Jittanit W Saeteaw N and Charoenchaisri A 2010 J. Stored Prod. Res. 46 209
[6] Sarker M Ibrahim M Aziz N and Salleh P 2014 Energy Convers. Manag. 77 389
[7] Suvanjumrat C and Loskupapaiboon K. 2020 Eng. J. 24(2) 2
[8] Suvanjumrat C 2017 Eng. J. 21(5) 225
[9] Suvanjumrat C 2016 Eng. J. 21(3) 207
[10] Chaiworapuek W Champagne J Y Hajem M E Kittichaikarn C 2010 AIP Conf. Proc. 1225 249
[11] Thungthong T Chalearmwattananon N Mongkolkitingam T and Chaiworapuek W 2020 Int. J. Heat Mass Transfer 163 1
[12] Zare D Naderi H and Ranjbaran M 2015 Dry Technol. 33 570
[13] Bhattacharya K Sowbhagya C and Swamy Y 1972 J. Sci. Food Agric. 23 171
[14] Ranjbaran M Emadi B and Zare D 2014 Dry Technol. 32 919
[15] Srivastava V and John J 2002 Energy Convers. Manag. 43 1689
[16] Roman F Schaefer V and Hensel O 2012 Biosystems Engineering 112(4) 359