EASR

# Engineering and Applied Science Research

https://www.tci-thaijo.org/index.php/easr/index

Published by the Faculty of Engineering, Khon Kaen University, Thailand

## Designing of the small mixed-flow dryer and studying of hot air distributions

Sitthiphon Sriwiset, Cherdpong Chiawchanwattana and Juckamas Laohavanich*

Postharvest Technology and Agricultural Machinery Engineering Research Unit, Mechanical Engineering Program, Faculty of Engineering, Mahasarakham University, MahaSarakham 44150, Thailand

Received 18 March 2021
Revised 22 April 2021
Accepted 18 May 2021

**Abstract**

The objective of this research is to design a mixed flow grain dryer for agricultural purposes at community level. The study focuses on the transmission of heated air within the drying chamber to design a drying system for thorough heating of grain. The drying chamber of the prototype has a width, length and height of 40, 50 and 120 cm, respectively. The dryer can hold 120 kg of grain with continuous drying. The 1 hp blower and 6 kW electric heater are used to generate hot air for drying. The hot air and moist air ducts are located in separate layers within the chamber. The moist air is then directed to the outlet. Each duct is in the shape of an equilateral triangle with a length of 6 cm. There are 10 layers with a spacing of 10 cm. Thermocouples were installed at the top, middle and bottom of the chamber to measure the temperature distribution. The results showed that the temperature distribution could be explained by the quadratic polynomial model with coefficients of determination ($R^2$) of 78.84%, 75.57% and 71.18% for the top, middle and bottom parts, respectively. The middle and lower parts of the chamber exhibited the most constant temperature. This prototype can operate under similar drying conditions as the large 30-40 m3 mixed flow dryer. Therefore, it could be used at the municipal enterprise level in the future.

**Keywords:** Mixed-flow dryer, Dryer design, Hot air distribution

### 1. Introduction

Rice (Oryza sativa L.) represents the most important food source in the world and is the staple food for the majority of the world's population [1]. In Thailand, rice is the major agricultural contributor to the Thai economy. More than 30 million tons of paddy are produced annually. Currently, there is a large agricultural extension project, in accordance with the Thailand 4.0 policy of the government. The aim is to help farmers modernize their farms by reducing production costs while increasing rice productivity and quality. Due to labor shortage, the method of rice cultivation has changed and machines such as combine harvesters have been introduced to save labor and reduce time [2]. Although the machines reduce the time required for harvesting, there are also disadvantages. For example, harvested rice has high moisture content and therefore needs to be dried before storage. Usually, drying is still done in the sun. Freshly harvested paddy has high post-harvest moisture content up to 20-25% [3, 4]. This freshly harvested grain with high moisture content needs to be dried to 12-14% to avoid quality deterioration due to microorganisms, insect infestation and respiration [5, 6]. Moreover, decay and respiration of paddy accelerates immediately after harvest due to high humidity and irregular sunlight [7]. Therefore, proper drying technique must be used to prevent rice decay and biological changes [8]. Drying of paddy is one of the most energy intensive operations [9]. The quality of milled rice, such as yield of head rice and visual color, is also significantly affected by drying methods [10].Currently, there are problems when harvesting occurs at the same time because there are not enough drying areas and some farmers have to use the government road or field to dry their rice. This causes social problems, conflicts or even accidents. In addition, some farmers state that the quality of rice obtained by drying in the field varies greatly and depends on many factors. For example, adverse weather conditions make the paddy is easy to deteriorate. For large mills, many types of hot air systems cannot be used because of the high capital cost. Guidelines for farmers can be found in the study by Puylaping and Thararux, [11] on a mobile simultaneous paddy dehumidifier using biomass fuel. After a dehumidification test on 800 kg of paddy with an initial moisture content of 33.58% (wb), the final moisture content was 14.24% (wb) and drying took eight hours. In the study by Wijanjak et al [12], a rotary dryer with infrared radiation combined with hot air injection was used to test the germination of white jasmine 105 with paddy. With an initial moisture content of 26% (wb) and a feeding rate of 100-200 kg per hour, the moisture content can be reduced to 16-20%(wb).According to the previous studies, mixed flow dryers provide good dehumidification performance in large mills. It is a suitable method for drying grain. Mixed flow drying is widely used in mills because it can reduce the fraction of broken grains and increase the percentage of whole grains. Since the dryer can use hot air and keep the rice cool, it can be used in conjunction with other types of dryers [13]. It is well known that even small changes in the process conditions or the properties of the rice grain can have a great effect on its quality. Mixed flow dryers (MFD) are commonly used to obtain a large mass flow of grain [14-16]. This type of energy efficient dryer can be introduced as an alternative dryer for drying paddy with high moisture to achieve high quality of milled rice in subtropical countries [17].This research considers the design of a mixed flow dryer for a joint venture.

*Corresponding author. Tel.: +668 1544 4408
Email address: juckamas.l@msu.ac.th
doi: 10.14456/easr.2022.9

The researchers believe that this could make the dryer more efficient and cost effective, which means that farmer groups and joint ventures will have adequate drying capacity. Therefore, the objective of this research work is to investigate the design guidelines for a mixed flow drying chamber, focusing on the heat transfer characteristics of the chamber to achieve an acceptable level of performance for industrial use. The results can be used as a guideline for the construction of a mixed flow dryer that is suitable for municipal operation and will benefit the Thai rice production industry in the future.

## 2. Materials and methods

### *2.1 Conceptual design of the compound flow dryer*

The structure of the mixed flow dryer consists of two main parts: a mixed flow drying chamber and a 6 kW electric heater. The blower works with a 1 HP motor (model AV -A112). Graphtec GL220 was used as data logger for temperature logging in this study. The working conditions for paddy require a drying rate of 240 kg per hour. It takes time for the rice to flow from the top of the drying drum to the bottom, resulting in a paddy flow rate of 30 minutes. The air velocity in the wind pipe is not more than 5 m/s, while the paddy density is 534 kg/m$^3$ [18]. The paddy flow rate in the drying chamber is 240 kg/hr. Along the zigzag line, 15 hot air inlet ducts and 10 wet air outlet ducts are installed, and the distance between the inlet and outlet ducts is 10 cm. The drying chamber measures 40 x 50 x 120 cm (width x length x height). There are three hot air ducts and two exhaust ducts in a three-sided shape with six centimeters on each side. The process of the mixed flow dryer is shown in Figure 1.

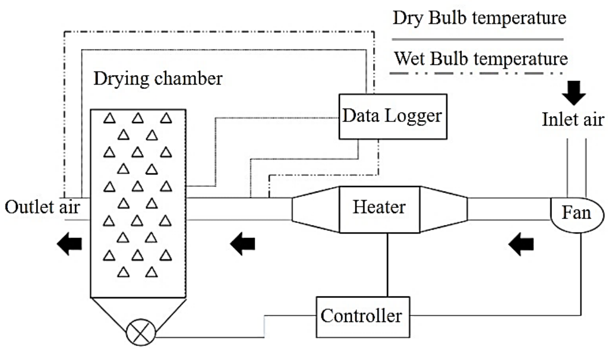


**Figure 1** Schematic diagram of a mixed-flow dryer.

The drying chamber is 120 cm long and has five layers, as shown in Figure 2. Accordingly, the volume of the drying chamber is 0.184 m$^3$. The design of the dryer provides the appropriate amount of warm air to dehumidify the paddy. A wind flow rate of 30-40 m$^3$ per minute, per m$^3$ paddy, is the most appropriate rate for the drying chamber. The total volume for the paddy is 0.184 m$^3$or 120 kg of rice. The amount of hot air required for drying is then equivalent to 5.62 m$^3$ per minute [19].

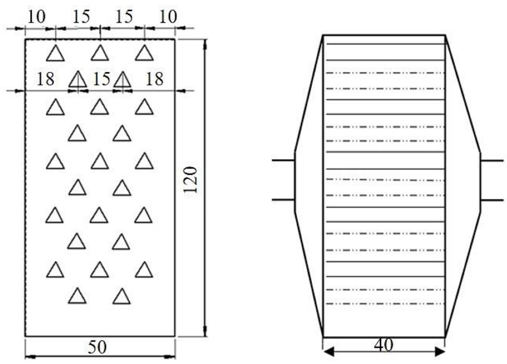


**Figure 2** Designed of a mixed-flow drying chamber.

### *2.2 Heat source design*

The size of the drying chamber in step 2.1 is determined by the initial conditions to provide the following:

- Average ambient air temperature = 27 °C
- Average relative humidity of ambient air = 80%
- Specific heat value of air $c_p$ = 1.013 kJ/kg dry air

According to the psychometric chart, the specific volume of air is 0.89 m$^3$per kg of dry air.

$$q = mc_p\Delta T \tag{1}$$

Where q = Heat content (kJ per minute)
m = Air mass flow rate (kg of dry air per minute)
$\Delta T$ = The difference in hot air temperature and ambient air (Celsius) to achieve the required amount of heat for drying is as follows:

$$q = \frac{5.62\text{m}^3/\text{min} \times 1.013 \times (60 - 27)°\text{C}/\text{kg dry} - \text{degree air}}{0.89\text{m}^3 \text{per kg dry air}}$$

$$= 275\ \text{kJ}/\text{min}\ (4.587\text{kW})$$

At 80% efficiency, the size of the heater should be about 5.733 kW to produce the hot air from combustion [20].

*2.3 Testing the heat dissipation inside the drying chamber*

The design of the drying chamber requires thorough heat dissipation to allow the degree of temperature distribution for the rice bark. An experiment was conducted to measure the hot air temperature distribution inside the drying chamber. In this study, the mixed flow dryer was tested for heat distribution at different positions within the drying chamber using Phitsanulok 2 rice variety as an example. The thermocouples were installed at different positions inside the vessel as shown in Figure 3. The temperature used in the test is 60 °C, which is the heat used in agricultural production for drying. Since this type of dehumidifier uses only hot air, the temperature is between 40 and 60 °C. However, the whiteness of rice is reduced depending on the temperature used, which is a trade problem when the temperature is higher than 60 °C [21]. The temperature is monitored at 27 points divided into three layers at the top (Plane A), middle (Plane B) and bottom of the dehydrator (Plane C) as shown in Figure 3, where the temperature is checked every five minutes until it reaches 125 minutes. The Tukey method considers all possible pairwise mean differences simultaneously, at a statistical confidence level of 95%.The joint influence of multiple factors on grain temperature is then analyzed to identify any discrepancies in the fitted model by looking at the $R^2$ of each model and testing the significance of the model term with the p-value and f-value. A model is created that predicts the results of the experiment in terms of a quadratic polynomial equation. The correlation of each factor is expressed using multiple regression analysis according to equation (2) under the appropriate conditions using a statistical program [1, 22-24].

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum\sum_{i<j} \beta_{ij} x_i x_j + \varepsilon \tag{2}$$

Where Y is the predictable variable
X is the primary variable.

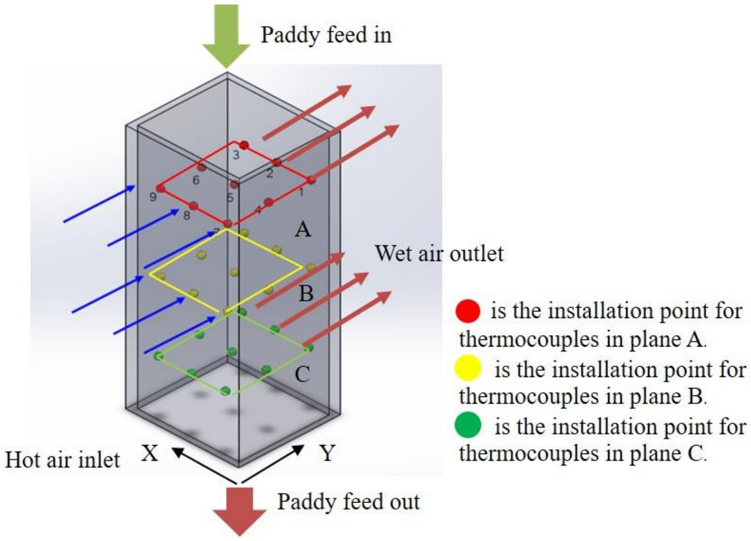


**Figure 3** Installation diagram showing the temperature measurement point at plane A, B and C in the drying chamber.

## 3. Results

*3.1 Results of the design of the mixed flow dryer for community enterprises*

The dryer measures 120 × 50 × 40 (width × length × height) and has three hot air ducts and two exhaust vents. The ducts are three-sided and measure 6 cm on each side, and the distance between each layer is 20 cm, for a total of five layers. The dryer requires 5.62 $cm^3$ of hot air per minute, with the heater set at 5.733 kW. The diagram in Figure 3 shows how the hot air flows into the dryer (represented by the blue arrows). The mixed flow plant for community farms contains a drying chamber. The rice flows by gravity from the top to the bottom of the bin. The flow rate is controlled by the control unit, with a bucket carrying the dried paddy grains out of the chamber area. The rice is then washed and ready to enter the continuous drying system. It is then dried with hot air from the 1 HP heater through a fan as shown in Figure 4.

*3.2 Temperature analysis in drying chamber*

The data were statistically analyzed using the Turkey's method at a 95% confidence level. The results show that after drying paddy grains for 100 minutes, the temperature in the chamber reached equilibrium. Subsequently, the surface model and contour plots for temperature were also analyzed. In the plane, pos X represents the chamber on the X axis. Where pos $X_1$ represents the edge of the chamber, pos $X_2$ represents the center of the chamber, pos $X_3$ represents the other edge of the chamber, and posY represents the Y axis. Where pos $Y_1$ denotes the air outlet side, pos $Y_2$ denotes the center of the bucket, and pos $Y_3$ denotes the air inlet side. The test results are shown in Table 1.

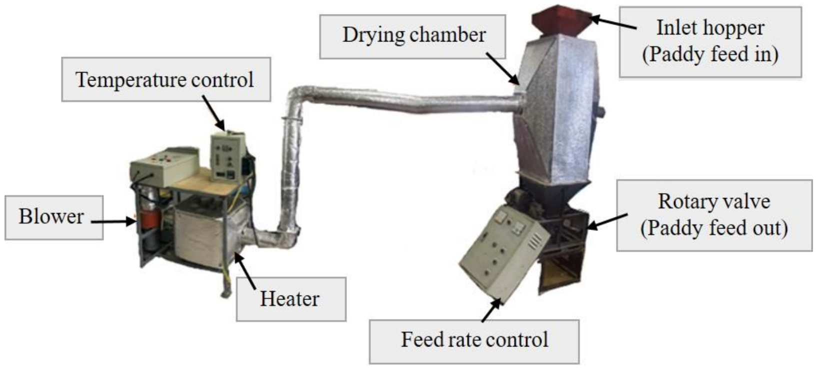


**Figure 4** Mixed-flow dryer for community enterprises.

**Table 1** Results of the temperature distribution test in the mixed-flow drying chamber

| Position | Average temperature (°C) | | |
|---|---|---|---|
| | **Plane (A)** | **Plane (B)** | **Plane (C)** |
| 1 | $42.2_f$ | $41.5_f$ | $39.6_f$ |
| 2 | $44.7_e$ | $46.1_e$ | $45.6_e$ |
| 3 | $42.2_f$ | $41.5_f$ | $39.6_f$ |
| 4 | $47.5_c$ | $46.9_c$ | $47.6_c$ |
| 5 | $44.8_d$ | $46.0_d$ | $45.7_d$ |
| 6 | $47.5_c$ | $48.8_c$ | $47.7_c$ |
| 7 | $50.9_a$ | $52.2_a$ | $55.7_a$ |
| 8 | $48.2_b$ | $49.4_b$ | $48.9_b$ |
| 9 | $50.9_a$ | $52.2_a$ | $55.7_a$ |

The a-f in the same column with different superscripts mean that the values are significantly different ($p < 0.05$).

*3.3 Mathematical model considerations*

In the top layer (plane A) of the drying chamber, the drying temperature can be explained by a quadratic polynomial equation with $R^2$ at 78.84% as follows:

$$\mathrm{temp_A} = 48.70 - 6.60\mathrm{posX} + 0.62\mathrm{posY} + 1.650\mathrm{X}^2 + 0.550\mathrm{posY}^2 \quad (3)$$

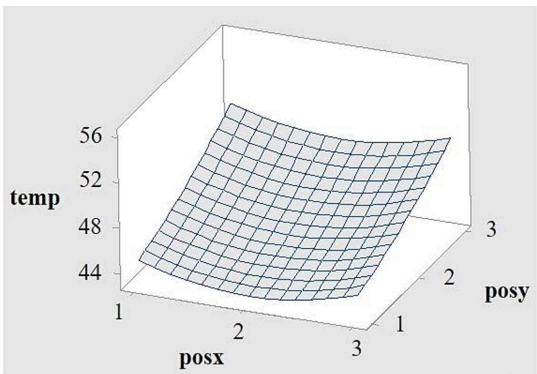


**Figure 5** Surface model showing the internal temperature of the plane an in drying chamber.

From Figure 5, it can be seen that the hot air enters from pos $Y_3$. The hot air then takes over the heat exchange in the air movement direction from pos $Y_3$ to pos $Y_1$, resulting in a high differential temperature gradient. This might be the plane is closed to the paddy feeder. When the rice is packed in the drying chamber, its two edges receive more ventilation than the center of the chamber in the center of the drying chamber was found to have a relatively low $R^2$ value when using a quadratic polynomial equation. Therefore, a quadratic polynomial equation cannot be used to describe the behavior of the air in the drying chamber. Therefore, the researcher uses the linear equation to describe the behavior within the middle layer (level B) and the floor (level C), where the $R^2$ of level B is 75.57%, as in the following equation.

$$\mathrm{temp_B} = 38.28 + 0.333\mathrm{posX} + 4.117\mathrm{posY} \quad (4)$$

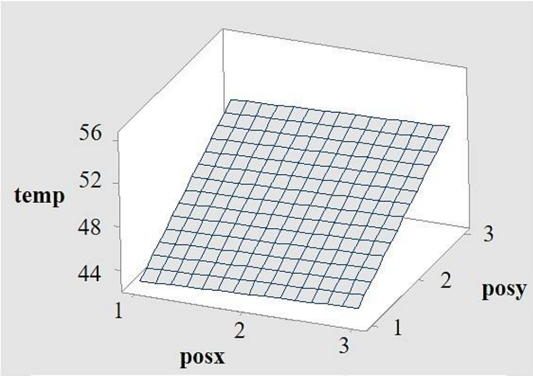


**Figure 6** Surface model showing the internal temperature of the plane B in drying chamber

As shown in Figure 6, the hot air enters the $posY_3$ side, and is then exchanged in the direction of the air movement from $posY_3$ to the point where $posY_1$causes a high-to-low temperature gradient. It has a more uniform heat distribution than Plane A due to the efficiency of the air distribution device and uniformity of the rice as well as a higher temperature. In the lower layer (Plane C), with a value of $R^2$at 71.18%, the behavior can be described with a straight-line equation as follows:

$$\text{temp}_C = 35.50 + 0.01\text{posX} + 5.92\text{posY} \quad (5)$$

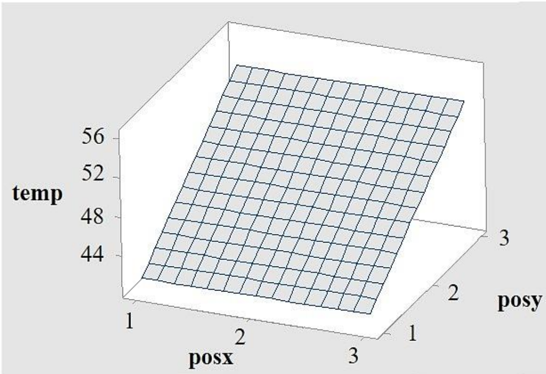


**Figure 7** Surface model showing the internal temperature on the plane C in drying chamber.

As indicated in Figure 7, the hot weather comes to $posY_3$. The hot air exchanges heat and air direction, moving from $posY_3$ to $posY_1$ thereby lowering the temperature. The heat is dissipated more uniformly than in planes A and B. The surface model shows that the temperature inside the drying chamber is in the plane C. It can be observed that the X axis has no effect on the temperature. The temperature affects the Y-axis, which shows the uniformity of air distribution. Then in the bottom plane, the temperature is higher than the other planes because the drying time is longer. The graphs of the horizontal temperature planes show a more uniform temperature distribution in plane A and plane B than in plane C. The distribution of hot air in the paddy drying chamber is heated and always moves from the upper part of the chamber to the lower part. This results in a uniform heat transfer throughout the drying time.

**4. Discussion**

The small mixed flow grain dryer for agricultural purposes was designed. In considering the hot air temperature distributions in this drying chamber as a design criterion, it was found that in plane A of the drying chamber, the drying temperature is very unevenly distributed. This is due to the fact that when rice is fed into the dryer, stacks form in the corners. This increases the temperature on both sides in the middle of the chamber, which has the greatest density, making it difficult for air to pass through. In plane B of the chamber, the hot air flows through the sides rather than the centre, which increases both temperature and drying time and results in better dispersion. Plane C of the drying chamber behaves similarly to plane B, but with a higher temperature due to a longer drying time and a more uniform temperature distribution. The dryer has good air distribution due to its design, so the paddy can be heated well. In addition, the paddy is always dry on its way from the top to the bottom, resulting in uniform heat transfer throughout the drying time. This result agrees with that of other researchers [25, 26]. These found that heating and drying is more intense for grain located near a series of air inlet ducts than for grain located near outlet ducts. However, drying time for both medium and thick paddy is higher when relative humidity is higher and lower at ambient temperature. The moisture content of paddy decreases with increase in drying time but the rate of decrease in moisture content becomes slower with increase in drying time. The same results were obtained by Barati et al and Tiwari et al [27, 28] in their study. This prototype could be adapted and applied at the social enterprise level in future. The setting of drying conditions is similar to that of a large-scale mixed flow dryer. Then, this drying technique can be used independently or in combination with another drying technique. For example, it can be used for dehumidification after grain drying when solar energy is not available for drying. In addition, it was found that the prototype is suitable to be used after the preheating step with infrared rotary dryer [29] after the preheating step to increase the temperature of the grains and then transfer them to the prototype mixed flow dryer. In this way, we can reduce the energy consumption and drying time while maintaining good quality of grain.

## 5. Conclusions

Based on the results of the tests, the design guidelines for the social enterprise level mixer dryer are as follows. The dryer measures 40 x 50 x 120 cm (width x length x height) with a maximum paddy capacity of 120 kg, a flow rate of 240 kg/h and a hot air velocity of 5 m/s. The temperature changes within the chamber can be explained by a quadratic polynomial equation with a decision coefficient ($R^2$) of 78.84%, 75.57% and 71.18% for the upper, middle and lower levels, respectively. The appropriate hot air velocity for the prototype dryer is 5 m/s, which is equivalent to a large 30-40 $m^3$ mixed flow dryer. Based on the study guidelines for the design of a mixed flow dryer for municipal operations, the dryer was finally found to be very functional and in accordance with the principle of mixed flow drying. It also behaves like a large-scale mixed-flow dryer. This prototype can operate with similar drying conditions as a large-scale mixed-flow dryer of 30-40 $m^3$. Therefore, it could be used at social enterprise level in the future.

## 6. Acknowledgements

This study was supported by a graduate research fellowship in agriculture and industry from The Agricultural Research Development Agency (Public Organization) fiscal year 2021.

## 7. References

[1] Laohavanich J, Wongpichet S. Drying characteristics and milling quality aspects of paddy dried with gas-fired infrared. J Food Process Eng. 2009;32(3):442-61.
[2] Ministry of Agriculture and Cooperatives. Large agricultural extension project [Internet]. 2018 [cited 2020 Jul 9] Available from: https://www.moac.go.th/news-preview-401591791369.
[3] Lilhare SF, Bawane NG. Drying rate analysis of different size paddy processed under various drying conditions in L.S.U Dryer. Int J Eng Res Tech. 2012;1(7):1-4.
[4] Jafari A, Zare D. Ultrasound-assisted fluidized bed drying of paddy: energy consumption and rice quality aspects. Dry Tech. 2017;35(7):893-902.
[5] Inprasit C, Noomhorm A. Effect of drying air temperature and grain temperature of different types of dryer and operation on rice quality. Dry Tech. 2001;19(2):389-404.
[6] Tirawanichakul S, Varanyanond W, Prachayawarakorn S, Tungtrakul P, Soponronnarit S. Effect of fluidized bed drying temperature onvarious qualityattributes of paddy. Dry Tech. 2004;22(7):1731-54.
[7] Dillahunty AL, Siebenmorgen TJ, Buescher R, Smith DE, Mauromoustakos A. Effect of moisture content and temperature on respiration rate of rice. Cereal Chem. 2000;77(5):541-3.
[8] Golmohamm M, Rajabi M, Hashemi SJ. Optimization of drying-tempering periods in a paddy rice dryer. Dry Tech. 2012;30(1):106-13.
[9] Ogura H, Hamaguchi N, Kage H, Mujumdar A. Energy and cost estimation for application of chemical heat pump dryer to industrial ceramics drying. Dry Tech. 2004;22(1-2):307-23.
[10] Prachayawarakorn S, Poomsa-Ad N, Soponronnarit S. Quality maintenance and economy with high-temperature paddy-drying processes. J Stored Prod Res. 2005;41(3):333-51.
[11] Puylaping N, Thararux Ch. Development and evaluation performance of a concurrent flow paddy dryer by using the biomass fuel. 12th Conference on Energy Network of Thailand; 2016 Jun 8-10; Phitsanulok, Thailand. (In Thai)
[12] Wijanjak S, Yangyuen S, Laohavanich J. Feasibility study of rotary dryer using infrared ray combined exhausted hot air in process of producing germinated brown rice. Agr Sci J. 2017;48(3Suppl):51-4. (In Thai)
[13] Vipattnaporn C, Yangyuen S, Laohavanich J. NIR Enhancement of a LSU dryer for maize. J Sci Tech MSU. 2016;35(6):626-9.
[14] Brooker DB, Bakker-Arkema FW, Hall CW. Drying and storage of grains and oilseeds. New York: Springer; 1992.
[15] Nellist ME, Bruce DM. Heated-air grain drying. In: Jayas DS, White NDG, Muir WE, editors. Stored-grain ecosystems. New York: Marcel Dekker Inc; 1995. p. 609-59.
[16] Muhlbauer W. Handbook of grain drying. Clenze: AgriMedia Verlag; 2009.
[17] Mondal HT, Pasha Shiplu KS, Sen K, Roy J, Sarker SH. Performance evaluation of small scale energy efficient mixed flow dryer for drying of high moisture paddy. Dry Tech Int J. 2019;37(12):1541-50.
[18] Sarker MSH, Ibrahim MN, Ab Aziz N, Punan MS. Application of simulation in determining suitable operating parameters for industrial scale fluidized bed dryer during drying of high impurity moist paddy. J Stored Prod Res. 2015;61:76-84.
[19] Khewkhom N, Laohavanich J, Wiset L. Pilot plant development factory for paddy drying using infrared ray combined with tempering and hot air for a small milling factory and effects of rice qualities and postharvest pest management [Internet]. Thailand: Agricultural Research Development Agency; 2013. [cited 2020 Jun 9]. Available from: https://www.arda.or.th/datas/download/detail08.pdf. (In Thai)
[20] Perry RH, Green DW, Perry S. Chemical Engineers’ Handbook. 8th ed. New York: McGraw-Hill; 2008.
[21] Preetong S. The study of factors affecting paddy drying process using the design of experiment [dissertation]. Chon Buri, Thailand: Burapha University; 2016.
[22] Laohavanich J, Yangyuen S, Thowjantuek N. An investigation of radiant heat distribution on drying area in the chamber of infrared rotary dryer. Adv Mater Res. 2014;1044-1045:232-5.
[23] Duangkhamchan W, Laohavanich J. Feasibility of using a multistage drying method including infrared heating, tempering and sun drying for wet paddy. Adv Mater Res. 2014;931-932:1497-501.
[24] Montgomery DC. Design and analysis of experiment. 8th ed. New Jersey: John Wiley &Sons; 2013.
[25] Giner SA, Bruce DM, Mortimore S. Two-dimensional simulation model of steady-state mixed-flow grain drying. Part 1: the model. J Agric Eng Res. 1998;71(1):37-50.

[26] Giner SA, Bruce DM, Mortimore S. Two-dimensional simulation model of steady-state mixed-flow grain drying. Part 2: experimental validation. J Agric Eng Res. 1998;71(1):51-66.
[27] Barati E, Esfahani JA. Mathematical modelling of convective drying: lumped temperature and distributed moisture in slab. Energy. 2011;36(4):2294-301.
[28] Tiwari GN, Singh AK, Bhatia PS. Experimental simulation of a grain drying system. Energ Convers Manag. 1994;35(5):453-8.
[29] Prakhethanang D, Chiawchanwattana C, Laohavanich J, Khaengkhan P, Yangyuen S. The influence of infrared radiation, hot air and the tempering on khao dawk mali 105 rice seedling germination and seedling growth. Thai Soc Agr Eng J. 2020;26(1): 52-61. (In Thai)